THE OPEN UNIVERSITY
A SCIENCE FOUNDATION COURSE

UNIT 9 ENERGY

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1.5

STUDY GUIDE

This Unit has three components: the text, an AV sequence and the TV programme 'Energy'.

The Unit begins, in Section 1, with a discussion of what is meant by 'the energy of an object' and Section 2 reviews some of the many forms energy can take. In Section 3, you will see that energy, like momentum (Unit 3), is the subject of a conservation law. The concept of energy conservation is then used, in Sections 4 to 9, to derive equations that allow us to calculate the changes in the energy of an object under various circumstances—for example, when it falls, is pushed, is heated up or is made part of an electric circuit. Most people have a feel for the concept of energy, even if they have not formulated their ideas in scientific terms before. Sections 4 to 9 make considerable use of this intuitive understanding through 'thought experiments'. You don't have to carry out any practical experiments while studying this Unit, but you will be required to draw many conclusions from your everyday experience! In addition, in the AV sequence, which makes up Section 7, you will bring together the concepts of energy and momentum and put the conservation laws to work in solving problems about collisions.

The TV programme 'Energy' may be watched with equal profit at any stage during your study of the Unit. This programme discusses many different forms of energy, shows how they may be converted one into the other, and illustrates the law of conservation of energy with some specific examples. You will therefore find references to the programme in almost every Section, although there are no separate TV notes.

1 INTRODUCTION

The subject of this Unit—energy—is one of the most important concepts in science, and one that is central to our understanding of natural phenomena. You will therefore find that many of the ideas introduced here are used over and over again in this Course, in connection with chemical reactions, biology, sub-atomic physics and many other topics.

It is often the case that a word has a different, more narrowly defined, meaning when used in a scientific context than when used in everyday speech. However, this is not true of the term 'energy': the scientific meaning of this word is very close to its colloquial meaning. What is implied by saying that someone is 'energetic'? The implication is that this person is (literally or metaphorically) always on the move and has a capacity for getting things done. In science too, an object is said to be energetic if it can do things. As a simple example, think of a ball. At rest on the ground, it can't do much: under these circumstances it is in a state of relatively low energy. You could, however, do things to the ball that would enable it, in turn, to influence other objects. You could, for instance, lift the ball up; if you then released it, it would fall and make a noise when it hit the ground. Alternatively, you could set it moving by kicking it; it could then break a window, knock over small objects and do many other things (Figure 1). In both these situations, the ball has *energy*. It is a basic belief of scientists that

FIGURE 1
Kicking a ball.

KINETIC ENERGY

GRAVITATIONAL ENERGY

ENERGY CONVERSION

CHEMICAL ENERGY

SOUND ENERGY

STRAIN ENERGY

HEAT

this energy doesn't just appear, but has to be *given* to the ball—in the first example this is done by lifting it and in the second by setting it in motion. Much of the rest of this Unit is concerned with explaining why we should believe that the ball's energy is not created but, instead, has to have been passed on from you to the ball.

We shall begin, in Section 2, by looking more closely at various ways of transferring energy to objects, and by identifying some of the most important types of energy.

2 ENERGY TAKES MANY FORMS

2.1 ENERGY DUE TO MOTION AND ENERGY DUE TO POSITION

Once the ball we considered in the previous Section has been dropped, or otherwise set in motion, its capacity to influence other objects is fairly obvious. The scientific term for this type of energy, which the ball possesses by virtue of its motion, is **kinetic energy.**

Our belief that energy does not simply appear as the ball starts to move, but is there as a result of something that happened to the ball, means that energy must somehow be given to the ball when it is lifted, and then stored in the ball when it is held above ground level: because of its position, the ball has the capacity to 'do' things—to influence other objects—although this capacity doesn't manifest itself until the ball is released. Thus the ball has 'hidden' (or stored), energy as a result of having been lifted against the gravitational force. This kind of energy, which is stored in the ball by virtue of its position in a region where it is subject to the pull of gravity, is called **gravitational energy***.

2.2 ENERGY CONVERSIONS

As you will see in later Sections, the concepts of kinetic energy and gravitational energy can be described quantitatively. First, however, it is worth looking again in a qualitative way at the example of the ball. How does its energy vary according to its situation?

At rest, the ball has no kinetic energy. If it is dropped from a height, it accelerates. The further it falls, the faster it will be moving and, if it hits the ground or another object, the more damage it will be capable of causing. From the intuitive 'definition' of energy we used in Section 1—the capacity to cause damage—we can say that the ball has more energy the faster it is going. In other words, the ball's kinetic energy increases with speed. Furthermore, because we believe that the ball has been given energy in the first place by being lifted against the pull of gravity, we can also say that the ball's gravitational energy increases with height.

The sequence of events is summarized in Figure 2. Just before it is released, the ball has gravitational energy but no kinetic energy. Half-way down it has acquired some kinetic energy, but its gravitational energy has decreased. The kinetic energy continues to increase and the gravitational energy to decrease, until the moment of impact with the ground. At this moment the ball's kinetic energy has its maximum value. The process has been one of continuous **energy conversion**, with gravitational energy being transformed into kinetic energy. Most of this Unit is concerned with identifying, and then quantifying, the energy conversions that take place in a wide variety of processes.

* In textbooks you will sometimes find this called *gravitational potential energy*, or just *potential energy*. Strictly speaking, however, the term potential energy encompasses many types of 'hidden' energy, of which gravitational energy is but one.

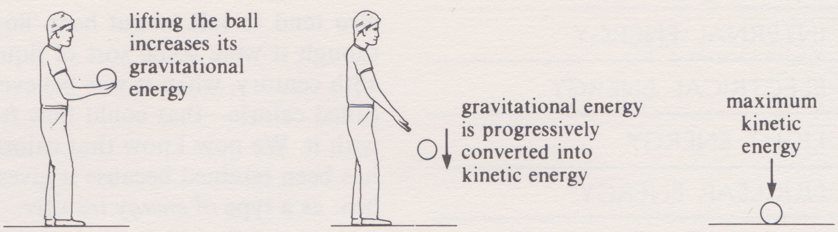


FIGURE 2 Energy conversions for lifting and dropping a ball.

2.3 SOME OTHER FORMS OF ENERGY

Thus far we have spoken in rather vague terms of the ball being 'given' gravitational energy when it is lifted, but it has also been asserted that energy doesn't appear from nowhere. So where *does* the ball's gravitational energy come from? The short answer is that it comes from the person doing the lifting: some of their 'muscular energy' is transferred to the ball, and converted into gravitational energy in the process. However, this is far from being the full story: the source of the energy can be traced back much further. The food you eat helps to keep you warm and is also the source of your energy. The process whereby the food is broken down and absorbed by your body is essentially a chemical (or, if you prefer, a biochemical) one, and may be thought of as the conversion of **chemical energy** into other forms of energy. You could of course go back one more step and ask how this chemical energy has come to be stored in the food. We will return to this point in Section 3.

Now think about what occurs at the other end of the sequence involving the dropped ball. What happens to its kinetic energy when it hits the ground? There is a thud: some of the ball's kinetic energy is convered into **sound energy.** In addition, the ball will be deformed, and while in this distorted form it will store energy as **strain energy.** As it bounces it returns to its previous shape, and the stored strain energy is converted back to kinetic energy. A similar energy conversion takes place when you stretch a rubber band: you have to supply energy to pull the two ends of the band apart, and the stretched rubber stores this as strain energy, which is converted into kinetic energy when you let go of one end of the band and it contracts back to its original length.

In Sections 2.4 and 2.5 we shall consider two other, quite different, types of energy. Before moving on, though, you might like to check that you can identify, in another situation, the various kinds of energy that we have already discussed. If so, try SAQ 1.

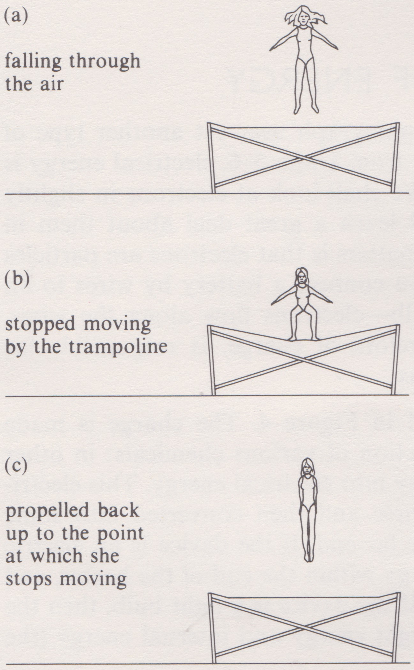


FIGURE 3 Sequence of events on a trampoline.

SAQ 1 Figure 3 shows a gymnast jumping on a trampoline. In (a) she is descending through the air and in (b) she has hit the trampoline and reached the lowest point. In (c) she has bounced back to a point at which she stops moving upwards. She will then fall back down again to the trampoline. What energy conversions have occurred during the sequence of events (a)–(c)?

2.4 INTERNAL ENERGY

Car handbooks tell us not to check tyre pressures immediately after a long run, because the tyres will be warm. Not all the chemical energy from the petrol is converted into the kinetic energy of the car: some of it is 'wasted' as heat in the engine and the tyres. Similarly, if you have ever played squash, you will know that when the ball has bounced a number of times, off the walls, the floor and your racket, it gets distinctly warm: on each impact the ball slows down slightly (i.e. its kinetic energy decreases) and some of the 'lost' energy is converted into **heat**.

In everyday language, there is a good deal of confusion about the word 'heat', because it often gets mixed up with notions of temperature (as, for instance, in the expressions 'blood heat', and 'this heat is unbearable'). We

also tend to talk about heat 'flowing' from a hot object to a cold one, as though it were some sort of liquid. This usage is actually a relic from the 18th century, when it was believed that there was indeed an invisible fluid–called caloric—that could flow from one object to another, conveying heat with it. We now know that caloric does not exist, but the idea of heat flow has been retained because it gives a vivid (and essentially correct) picture of heat as a type of *energy transfer*.

Imagine putting a metal spoon in a cup of boiling coffee. The spoon would warm up (in fact, it would soon become uncomfortably hot to hold) and the coffee would cool down very slightly. Heat would thus be transferred from the coffee to the spoon, which is equivalent to saying that the energy of the spoon would increase, while that of the coffee would decrease. This type of energy, which increases when a substance warms up and decreases when the substance cools down, is called the **internal energy** of the substance.

We shall return to a more detailed discussion of the distinction between heat, temperature and internal energy in Section 8. However, this brief introduction should at least have shown you how to avoid the confusion created by the colloquial use of the word heat. In scientific usage, it is correct to talk about heating the water in your electric kettle—this is simply shorthand for 'transferring energy to the water and so causing its temperature to rise'. It is *not* strictly correct to refer to the *heat in* the water when what you really mean is the *internal energy of* the water.

2.5 YET MORE FORMS OF ENERGY

The kettle referred to in the previous paragraph uses yet another type of energy—**electrical energy**. As you know from Units 5–6, electrical energy is associated with the flow of electrons. We shall look at electrons in slightly more detail in Section 9, and you will learn a great deal about them in Units 11–12. For the moment, all that matters is that electrons are particles with the property of 'charge'. When you connect a battery by wires to an electrical device—say a kettle or a bulb—electrons flow along the wires. This movement of electrons, and therefore of charge, is responsible for transferring electrical energy to the device.

The various processes are summarized in Figure 4. The charge is made available within the battery by the reaction of various chemicals: in other words a battery converts chemical energy into electrical energy. This electrical energy can be transferred along wires and then converted into some other form of energy by a device at the far end. If the device is an electric kettle, the conversion is to internal energy within the coil of the heater, and thence to internal energy of the water. If the device is a light bulb, then the electrical energy will be converted to **light energy** and internal energy (the light bulb will get hot).

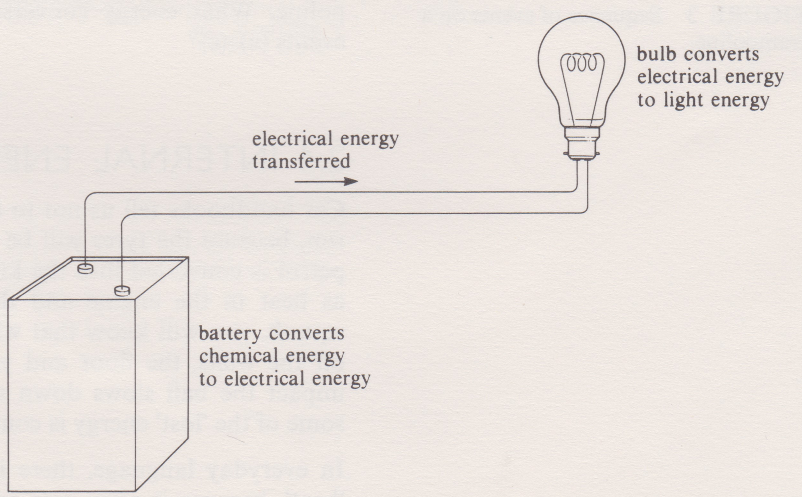


FIGURE 4 Energy conversions in an electric circuit.

ITQ 1 In most homes, electric light bulbs are run not from batteries, but from the mains. Identify the principal energy conversions involved in lighting your house if (a) you are in an area served by a coal-fired power station and (b) you are served by a hydro-electric scheme.

In the domestic examples in ITQ 1, the various energy conversions eventually supply us with a certain amount of light energy. However, light energy is not necessarily the end of a chain of energy conversions—it can also be the beginning. The light energy we receive from the Sun is converted by the process of photosynthesis in green plants (which you will study in Units 22–23) to chemical energy, which is stored in the plants. At this very moment, you are able to read the words on this page because light energy is being converted to chemical energy in your eyes and then to electrical energy, which is activating nerve impulses to your brain.

While thinking about the Sun, brief mention must be made of one more type of energy: **nuclear energy**. This kind of energy is converted in both 'fusion' reactions (which take place in the Sun and other stars, and are used in thermonuclear weapons) and 'fission' reactions (which are used in nuclear power stations and atomic bombs). You will come across nuclear reactions again in Unit 31.

The list of types of energy given in this Section is not exhaustive, but it does cover most forms of energy encountered in everyday situations, and provides a basis for the more quantitative investigation of energy that makes up most of the rest of this Unit.

SUMMARY OF SECTION 2

There are many forms of energy. An object can possess some types of energy because of where it is or what has been done to it: *gravitational* energy and *strain* energy fall into this category. An object can also possess energy by virtue of the fact that it is moving: this is called *kinetic* energy. Energy may be transferred to or from a substance in the form of heat and such a transfer causes a change in the *internal* energy of the substance, which is related to its temperature. Other important types of energy include *chemical* energy, *electrical* energy, *light* energy, *sound* energy and *nuclear* energy.

Before moving on, you may like to try another SAQ, which tests whether you can account for the energy conversions in a short sequence of events.

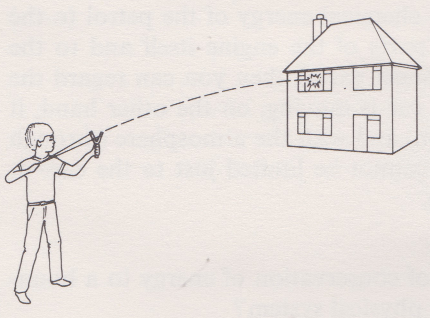


FIGURE 5 Catapulting a stone.

SAQ 2 A small boy fires a stone with a catapult and it breaks a neighbour's window (Figure 5). Starting with the energy needed to stretch the rubber in the catapult, describe the energy conversions that take place in this disgraceful incident.

3 ENERGY IS ALWAYS CONSERVED

3.1 INTRODUCTION

By now you should be getting the idea that the story of energy conversions has no beginning and no end. You saw in Section 2.5 that, by the process of photosynthesis in green plants, the light energy from the Sun is converted into chemical energy. As you will see in Units 22–23, this chemical energy is used to remove carbon dioxide from the atmosphere and to return oxygen to it, enabling plants to assimilate carbon and to grow. Over millions of years, accumulations of dead plants turn into peat or coal or oil, which we can burn in power stations, recovering that long-stored energy and converting it to electrical energy which we can then use to heat and light our

LAW OF CONSERVATION OF ENERGY

homes. And where did the light energy that started off this chain of conversions originate? From the Sun, where nuclear energy is continuously being converted into light energy. How did the nuclear energy come to be stored in the Sun? Well that too is traceable, back to the origins of the Universe, which you will look at later in the Course (Unit 32).

We could follow such sequences endlessly, finding out where a particular form of energy has come from, and identifying the forms into which it is converted. At first sight, this might seem to be little more than a classification exercise, but the results are of enormous significance: the implication of never-ending chains of energy conversions is that energy cannot be created out of nothing—it can only be made available in a particular form as a result of energy transfers or conversions. This suggests a basic question: given a certain amount of energy in one form, how much of it can be converted into other forms? The answer, very simply, is *all* of it. Underlying this assertion is a fundamental scientific law—the law of conservation of energy.

3.2 THE LAW OF CONSERVATION OF ENERGY

A concise statement of the **law of conservation of energy** is

> the total amount of energy in a physical system is always constant.

More informally, we can say that at every stage in a chain of energy conversions within a particular system the total amount of energy is always the same: *energy cannot be created or destroyed.* No process has ever been found that violates this law.

To understand this law fully, you must first be clear about what is meant by a 'physical system'. This is simply shorthand for 'a system (i.e. an object or group of objects) that is isolated from its surroundings'. Take the example of a car. If it is stationary and if you are interested only in the workings of its engine (i.e. in the conversion of the chemical energy of the petrol to the kinetic energy of the various moving parts of the engine itself and to the kinetic and internal energies of the exhaust gases), then you can regard the engine as a physical system. Once the car is moving, on the other hand, it interacts with the road (through friction) and with the atmosphere (through air resistance), so the physical system cannot be limited just to the car—it must include car, road and atmosphere.

ITQ 2 If you were applying the law of conservation of energy to a bouncing ball, what would you take as your physical system?

To see what energy conservation means in practice, let us now compare two simple physical systems. Let's suppose the first consists of a metered electricity supply to your home plus a fluorescent strip-light, and the other consists of the metered electricity supply plus a bulb with a tungsten filament. If you were to use a particular amount of energy (as indicated by the meter) to run the fluorescent strip and exactly the *same* amount of energy to run the bulb, you would find that the fluorescent strip gave *more* light for your money than the bulb.

How does the law of energy conservation cope with this observation? Well, it *predicts* that at least one of the lights must have converted some of the energy supply into another form of energy besides light energy. If both lights had converted the same amount of electrical energy completely into light energy, then they would both have given the same amount of light energy.

Is this prediction borne out in practice? Anybody who has ever changed a light bulb knows that bulbs get very hot after they have been on for a while.

So, in a qualitative sense, we can say that the prediction is fulfilled: light bulbs convert electrical energy into light energy plus the internal energy of the filament and outer casing.

However, the law of conservation of energy goes far beyond the *qualitative* predictions we have made so far. If you know how much energy was supplied and what proportion of this was converted into light energy, the law enables you to work out the increase in internal energy of the bulb (assuming that no other form of energy is produced). Imagine, for example, running a fluorescent light using one unit of electrical energy and finding that the tube's temperature was unchanged and that it was silent in operation. The law of conservation of energy then leads you to say that all the electrical energy supplied has been converted to light energy (Figure 6a). Note that in this thought experiment we imagined an 'ideal' fluorescent tube (i.e. one that converts all the electrical energy to light energy); in practice, no device converts electrical energy into light energy with 100% efficiency. So now let us imagine a more realistic scenario: suppose you supplied a tungsten filament bulb with one unit of electrical energy and found that only 10% of this (0.1 unit) was converted into light energy. Then the law of conservation of energy tells you that the other 0.9 units must have been converted to some other form of energy (Figure 6b). You might predict that all the 0.9 units should appear as internal energy, and you could test your prediction quantitatively. If you found the internal energy of the system as a whole had increased by less than 0.9 units, you would move on to consider other possible energy conversions, such as that of electrical energy to sound energy. In the end, you would find that the 0.9 units were accounted for: no process has ever been discovered in which energy is not conserved, to within the limits of experimental uncertainty.

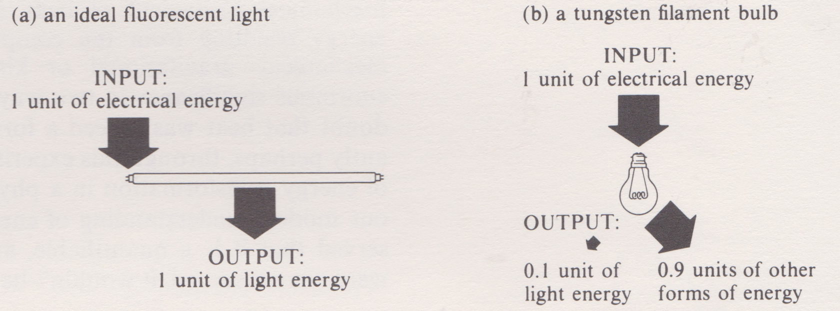


FIGURE 6 Comparison of the input and output of an ideal fluorescent light with that of a tungsten filament bulb. In both cases, energy input = energy output.

ITQ 3 Suppose you supplied ten units of electrical energy over a certain time to a single-bar electric fire and found that the increase in internal energy of the bar over this time was six units. What conclusions would you draw?

By now you may have an uncomfortable feeling that the way the law of energy conservation has been applied is just a trick. If we look at a process and find that the energy input isn't exactly equal to the energy output, we simply 'invent' another form of energy to make the books balance! However, there's much more to it than that. If we define a new form of energy in order to account for what would otherwise be an energy deficit in some particular process, then that definition must be universally applicable. *From then on we must always use the definition of that form of energy and calculate its contribution to other processes in the same way.* If our initial assumptions were fallacious we would soon come up against a contradiction. As yet this has never happened. Applying the law of energy conservation consistently, scientists have defined 'new' forms of energy (such as nuclear energy, discovered only within the last 50 years), but these have never led to conclusions that contradict the law. It is a basic tenet of scientific belief that, whatever presently undreamed-of physical processes we may discover in the future, there is a quantity that will remain constant throughout these processes—the quantity we call energy.

3.3 THE MOST IMPORTANT PHYSICAL LAW?

The importance of a physical law can, to some extent, be gauged by the insights it gives into the way nature operates—especially if those insights are difficult or impossible to gain in any other way. From this point of view, energy conservation is arguably the most useful physical law ever formulated.

So what is it about the idea of energy conservation that makes it so useful? Well for one thing, it brings together many phenomena that would otherwise seem unrelated: it *unifies*. As shown in the TV programme, the English physicist James Joule made a major contribution in pointing this out. During the first half of the 19th century, a bewildering variety of new effects and processes had been discovered: Volta had demonstrated the first battery, which produced electricity from a chemical reaction; other scientists had gone on to show that an electric current could give rise to heating, lighting and magnetic effects, and that it could initiate chemical reactions in the process called electrolysis. In 1822, Seebeck generated an electric current by joining two different metals heated to different temperatures. In 1831, Faraday showed how to induce an electric current in a wire by moving it in a magnetic field. Nowadays we realize that all these processes can be quantitatively described using the law of conservation of energy, but at the time of their discovery they seemed to be a collection of unconnected phenomena. It was Joule who, in 1847, took the first step in linking them by putting forward the idea of *conversion*, a process whereby 'something' is qualitatively transformed while nevertheless being quantitatively conserved. We now refer to this 'something' as energy. One of Joule's most important experiments is reconstructed in the TV programme and will be discussed in detail in Section 8, but it is appropriate to summarize his conclusions here. What Joule did was to define and actually *measure* what he called 'the mechanical equivalent of heat' (in other words, the change in internal energy resulting from the complete conversion of a known amount of mechanical—gravitational or kinetic—energy). This experiment was of enormous significance in two ways. For one thing it demonstrated beyond doubt that heat was indeed a form of energy transfer. Even more importantly perhaps, through this experiment Joule gave a *quantitative* description of energy transformation in a physical process and thus paved the way for our modern understanding of energy. It is precisely *because* energy is conserved that it is a quantifiable, and therefore measurable, parameter. If it were not conserved, it wouldn't be of much interest!

It is difficult to emphasize enough the importance of energy conservation as a unifying principle. The excitement that the 19th-century scientists felt when they realized the power of this idea was expressed by Joule himself in these words:

> Indeed the phenomena of nature, whether mechanical, chemical or vital*, consist almost entirely in a continual conversion of attraction through space†, living force‡ and heat into one another. Thus it is that order is maintained in the universe—nothing is deranged, nothing ever lost, but the entire machinery, complicated as it is, works smoothly and harmoniously. And though . . . everything may appear complicated and involved in the apparent confusion and intricacy of an almost endless variety of causes, effects, conversions, and arrangements, yet is the most perfect regularity preserved. (Joule, J. P. (1884) *The Scientific Papers of James Prescott Joule, Volume 1*, London, Taylor and Francis, p. 273.)

* By 'vital' Joule meant 'relating to life'.
† In modern terminology we should call 'attraction through space' gravitational energy.
‡ It is debatable what Joule intended by 'living force': he may have been thinking of what we would nowadays call (bio)chemical energy or he may simply have been refering to kinetic energy.

SUMMARY OF SECTION 3

The law of conservation of energy states that the total energy in any physical system is always constant. Energy may be transferred from one object to another, or converted from one form into another, but it is never created out of nothing, nor is it ever destroyed.

It is the law of conservation of energy that allows us to balance the energy inputs and outputs for a particular system, and so to make energy quantitative (i.e. measurable). If energy were not conserved it wouldn't be a useful concept—at least not useful enough for a whole Unit of this Course to be devoted to it!

SAQ 3 We are continually being exhorted to 'save energy', and advertisements highlight any energy-saving features of domestic applicances. Why is this thought to be important, if energy is always conserved anyway?

4 MEASURING ENERGY

So far you have been asked to accept the fact that the amount of energy in a system can be determined quantitatively. In this Section we shall take things one step further by discussing how we might actually go about measuring the amounts of energy converted in a particular process, and the units we should use. Then, in subsequent Sections, we shall go on to develop equations that will enable us to calculate energy changes in a wide variety of situations.

4.1 THE ENERGY TRANSFERRED BY A CONSTANT FORCE

Let's begin with an everyday problem. Imagine you have to tow a car along a flat road. Assuming you have some means of applying a constant (pulling) force to the car, how much energy would you use in moving it a given distance? Common sense probably tells you that the energy you would have to supply would depend on the *magnitude of the force*, F, required to keep the car moving at all (i.e. to balance the opposing frictional forces) and on the *distance* you moved it. So, is the energy proportional to $F \times$ distance, or $F^2 \times$ distance, or $F \times (\text{distance})^2$, or what? To find out we would need to do an experiment.

The 'apparatus' for this experiment is illustrated in Figure 7. The car is towed by a lorry along a flat road. Between the two vehicles is a device that measures the magnitude of the force being applied to the car. If the lorry moves at constant speed in a straight line with the tow-rope remaining taut, then the car will move with the same constant speed in the same direction. In this situation, in which the car has no acceleration, Newton's second law tells us that there is no net force on the car. In other words, the force the lorry exerts on the car and the various frictional forces are exactly balanced.

The energy used to tow the car is provided by the fuel (chemical energy) in the lorry's tank. The lorry itself requires a certain amount of fuel if it is to move. Hence, the energy required to move the car as well is measured by the *extra* fuel consumed by the lorry in pulling the car.

To find out how the energy required to pull the car along depends on the distance travelled and on the magnitude of the force, you would have to do

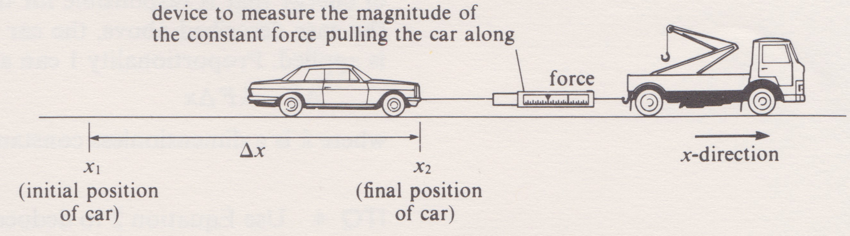


FIGURE 7 Towing a car.

JOULE

ELECTRONVOLT

two experiments: one to find out how the energy required varies with the distance that the car travels, and the other to see how it varies with the force that pulls it along.

In one of these experiments, you would have to keep the magnitude of the force constant, so as to be sure that any variation you measured in the energy required to pull the car along had nothing to do with variations in the force. Similarly, to find out how the energy required depends on the force that pulls the car along, you would need to carry out a second experiment, in which you varied the force but kept constant the distance over which the car was pulled. Let us consider these in turn as thought experiments.

Take first the case in which the magnitude of the pulling force is constant (and the force is always in the same direction).

□ Would you expect the energy transferred to the car to increase or to decrease with the distance that the car is pulled?

■ Most people intuitively (and correctly) expect that the further the car is pulled, the more energy is required. In fact, experiments show that the energy transferred to the car is directly proportional to the distance it travels (provided the force pulling it is of constant magnitude).

Suppose that we call the direction in which the car moves the x-direction. If it is pulled a distance Δx (from position x_1 to position x_2) and energy ΔE is transferred to it, then

$$\Delta E \propto \Delta x$$

The quantity on the left-hand side of this expression is said as 'delta E'. The delta notation is commonly used in science to denote a *change* in the value of some quantity: thus ΔE for a change in the energy of the car, Δx for a change in position, ΔT for a change in temperature, Δh for a change in height, and so on.

Now think about how the energy required to pull the car along depends on the force pulling it. (One way in which you could vary the magnitude of the force required to pull the car at a constant speed would be to leave the car's brakes slightly, but permanently, on.)

□ Would you expect the energy required to pull the car along to increase or to decrease if the magnitude of the pulling force were to increase (with the distance that the car is pulled kept constant)?

■ If the magnitude of the force were to increase, then the energy required to pull the car along would also be expected to increase.

The results of experiments show that the energy transferred, ΔE, is directly proportional to the magnitude of the force, F (provided the distance that the car travels is kept constant):

$$\Delta E \propto F$$

So the energy converted in pulling the car along, ΔE, is directly proportional to both F and Δx:

$$\Delta E \propto F \quad \text{and} \quad \Delta E \propto \Delta x$$

These statements can be combined into one:

$$\Delta E \propto F \times \Delta x \tag{1}$$

that is, the energy required is proportional to the product of the magnitude of the force and the distance travelled. This is true irrespective of the form of energy that is responsible for the moving of the car, provided that, as in the case described above, the car moves in the direction in which the force is applied. Proportionality 1 can also be written in the form of an equation:

$$\Delta E = kF\,\Delta x \tag{2}$$

where k is a dimensionless constant of proportionality.

ITQ 4 Use Equation 2 to deduce the *dimensions* of energy.

4.2 UNITS OF ENERGY

Equation 2 can also be used to define the *units* in which energy is measured. Thus

1 unit of energy = k × (1 unit of force) × (1 unit of distance)

In SI units, the constant k is chosen to be dimensionless and to have a value of one, so that

1 SI unit of energy = (1 SI unit of force) × (1 SI unit of distance)

Provided that we stick to SI units, Equation 2 can therefore be written as

$$\boxed{\Delta E = F\,\Delta x} \tag{3}$$

In recognition of the enormous contribution James Joule made to this area of science, the SI unit of energy is named after him:

1 joule = 1 newton × 1 metre

The **joule** is thus defined as the amount of energy transferred by a constant force of magnitude one newton when it moves through a distance of one metre in the direction of the force.

$$1\ \mathrm{J} = 1\ \mathrm{N} \times 1\ \mathrm{m}$$

$$\boxed{1\ \mathrm{J} = 1\ \mathrm{N\ m}} \tag{4}$$

Incidentally, note that, like the newton, the joule is abbreviated by a capital letter, although when spelled out in full its initial letter is lower case.

So how large an amount of energy is a joule? Well, it is roughly the amount of kinetic energy that an eating apple acquires by the time it hits the ground having fallen off a table. To take a different example, the energy required to stretch a thin rubber band 10 cm long to three times its natural length is about 0.2 J. If you happen to have a rubber band handy, try stretching it to triple its length, just to get an idea of what it feels like to transfer this quantity of energy. One joule is really quite a small amount of energy. Table 1 (overleaf) quantifies the energy associated with a few other real-life events.

As you work through the next few Sections, you will be able gradually to add further examples to Table 1. The first such example is contained in ITQ 5.

ITQ 5 You lift a 5 kg bag of potatoes vertically upwards from the floor and place it on a work-surface that is 1 m high. What energy transfers or conversions have taken place? Once the manoeuvre has been completed, by how much has the energy of the bag of potatoes increased? Enter your result in Table 1. (*Hint:* first work out the minimum force you would have to apply, assuming this to be of constant magnitude; take the magnitude of the acceleration due to gravity, g, as 10 m s^{-2}.)

Although the joule, being the SI unit, is the unit of energy most commonly used in science, it is rather too large to be convenient in discussions involving energy conversions at the atomic level. In such circumstances, physicists and chemists often use a unit called the **electronvolt** (abbreviated as eV).

$$1\ \mathrm{eV} \approx 1.602 \times 10^{-19}\ \mathrm{J}$$

We shall examine this unit of energy in more detail in Section 8. In later Units, you will see how useful the electronvolt can be in describing the energy changes involved in atomic or sub-atomic processes.

In addition to the joule and the electronvolt, there are other units of energy that are in widespread everyday use, although they are not commonly used

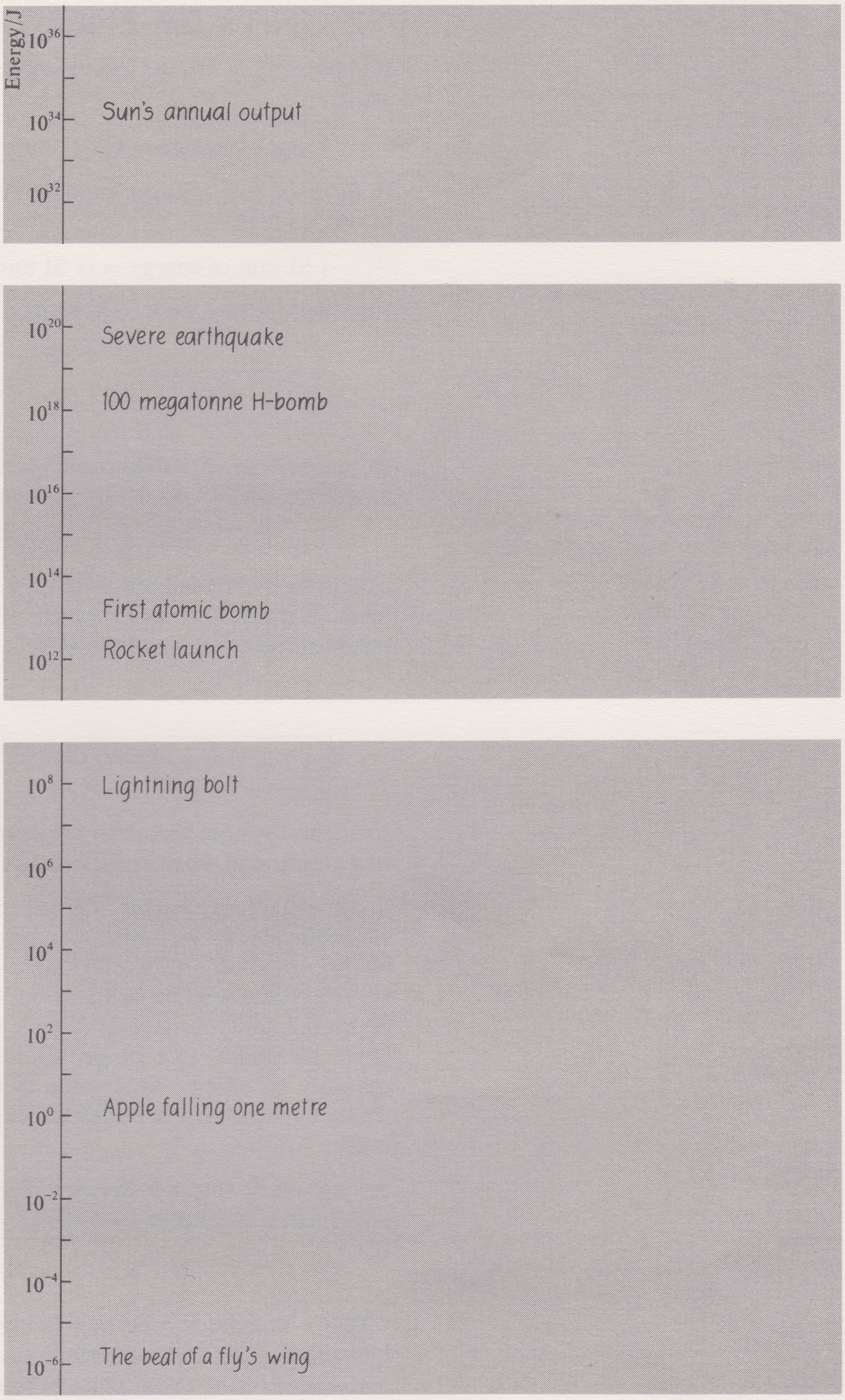


TABLE 1 The energies associated with various events.

by scientists. The joule is rather too small a unit to be convenient in measuring the energy requirements of the average household. You will therefore find that your gas and electricity bills are drawn up, not in terms of joules, but in therms and kilowatt-hours (kW h) respectively:

$$1 \text{ therm} \approx 1.055 \times 10^8 \text{ J}$$

$$1 \text{ kW h} = 3.600 \times 10^6 \text{ J}$$

We will meet kilowatt-hours again in Section 8.

ITQ 6 Information about the energy content of food is usually given in terms of a unit called the calorie, defined such that 1 kcal $\approx 4.2 \times 10^3$ J. Books about diet and nutrition tell us that a slice of bread 'contains' about 60 kcal. How many joules do you convert when you digest and absorb one slice of bread? Enter your result on Table 1.

SUMMARY OF SECTION 4

1 When, under the influence of a constant force of magnitude F, an object moves a distance Δx in the direction of the force, the amount of energy ΔE transferred to the object is given by the equation

$$\Delta E = F\,\Delta x$$

where all the quantities are in SI units.

2 The dimensions of energy are those of

$$\text{mass} \times (\text{length})^2 \times (\text{time})^{-2}$$

3 The SI unit of energy is the joule, defined as the amount of energy transferred or converted when a constant force of magnitude one newton moves an object through a distance of one metre in the direction of the force:

$$1\text{ J} = 1\text{ N m}$$

Another important unit of energy, much used in discussions of atomic processes, is the electronvolt:

$$1\text{ eV} \approx 1.602 \times 10^{-19}\text{ J}$$

SAQ 4 (a) In pushing a shopping trolley at constant speed in a straight line for a distance of 20 m across a smooth floor in a supermarket, you exert a force of 5 N in the direction of motion of the trolley. How much energy have you transferred?

(b) Is the kinetic energy of the trolley exactly equal to the energy you transfer? Explain your answer.

5 GRAVITATIONAL ENERGY

Now that we have defined an energy scale (based on the joule), we are in a position to see how to calculate the amounts of energy involved in some important processes. We'll begin with gravitational energy, since in fact you already know how to calculate this!

5.1 A FORMULA FOR GRAVITATIONAL ENERGY

Think back to ITQ 5, which was about lifting a five kilogram bag of potatoes through a vertical distance of one metre. You calculated the increase in energy of the bag as a result of its having moved from a stationary position on the ground to a stationary position one metre higher. Effectively, therefore, you worked out the increase in *gravitational* energy of the bag by using Equation 3. This stated that (in SI units) for an object moved by a constant force in the direction in which the force is applied,

energy transferred to the object =

magnitude of force required to move object × distance moved

In the case of an object of mass m lifted through a height Δh (Figure 8), Newton's second law states that the magnitude of the force required to move the object at constant speed is mg, where g is the magnitude of the acceleration due to gravity at that site. The energy transferred to the object is therefore mg times Δh and this is equal to the change in gravitational energy, ΔE_g, of the object:

$$\boxed{\Delta E_g = mg\,\Delta h} \qquad (5)$$

Don't lose sight of the fact that it was the law of conservation of energy that enabled us to derive this expression!

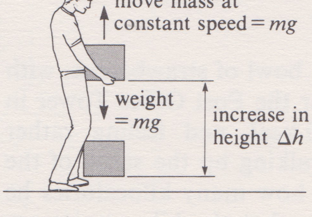


FIGURE 8 When the mass m is lifted through a vertical distance Δh, its increase in gravitational energy, ΔE_g, is given by $mg\,\Delta h$.

5.2 GRAVITATIONAL ENERGY IS ALWAYS RELATIVE

Quantities such as length, mass or force have absolute values, in the sense that we can say, for example, 'this object is two metres long'. Gravitational energy, on the other hand, does not have an absolute value. We cannot say that an object possesses gravitational energy of so many joules. All we can say is that if it were to fall a certain distance Δh then an amount of energy equal to $mg\ \Delta h$ would be converted into other forms of energy. Once the object has reached the ground, it can't fall any further, but that still doesn't imply that its gravitational energy is zero. We could start with the object at ground level and drop it down a mine shaft. Once again, it would fall, with a conversion of gravitational into kinetic energy.

No physical significance can be attached to the *absolute* value of an object's gravitational energy at one particular point. When the object falls from some starting point to a lower one, it is the *difference* between its gravitational energy at the two points that is converted into kinetic energy. The absolute value of the gravitational energy is arbitrary and it doesn't matter where you specify the zero of gravitational energy to be. Mind you, we shall often find it useful to specify the ground as the position of zero gravitational energy, but you should be in no doubt that this is a matter of convenience, not a physical necessity.

In short, it doesn't matter what point you choose for the zero of gravitational energy—all that matters is how far the object falls, and how much energy is converted to other forms as a result of that fall. Physicists do often talk of an object 'having' a certain amount of gravitational energy, but this is just a (sloppy) short-hand way of saying that if the object were to fall (usually to the ground), that amount of energy would be converted to other forms. It certainly makes no sense to talk about the gravitational energy of an object without saying with respect to what point it has that energy. For example, the fairground swingboat shown in the TV programme and illustrated in Figure 9a 'has' gravitational energy $mg(d + \Delta h)$ with respect to the ground, but $mg\ \Delta h$ with respect to the lowest point P of its arc of swing. In solving problems concerned with the motion of the swingboat, it may be convenient to *assign* it zero gravitational energy when it is at point P (Figure 9b), but it will nevertheless have gravitational energy mgd with respect to the ground.

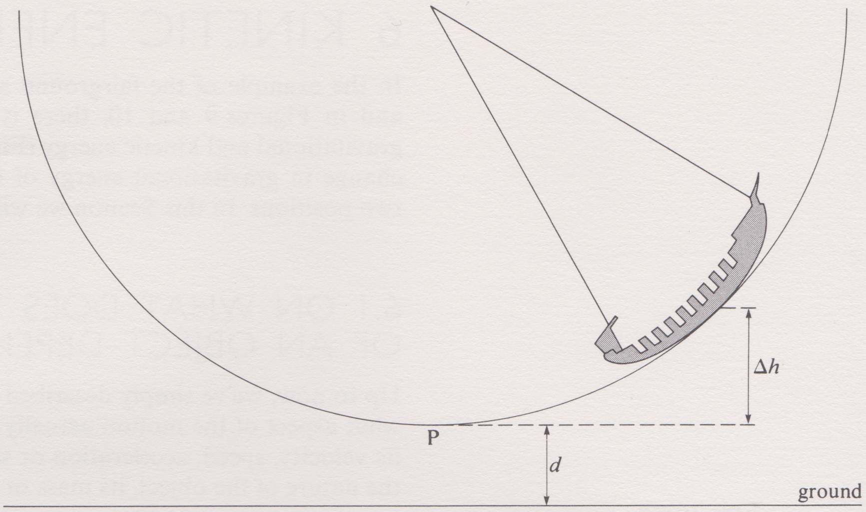
SUMMARY OF SECTION 5

An object of mass m positioned a vertical distance Δh above a fixed point 'has' an amount of gravitational energy ΔE_g with respect to that point, given by

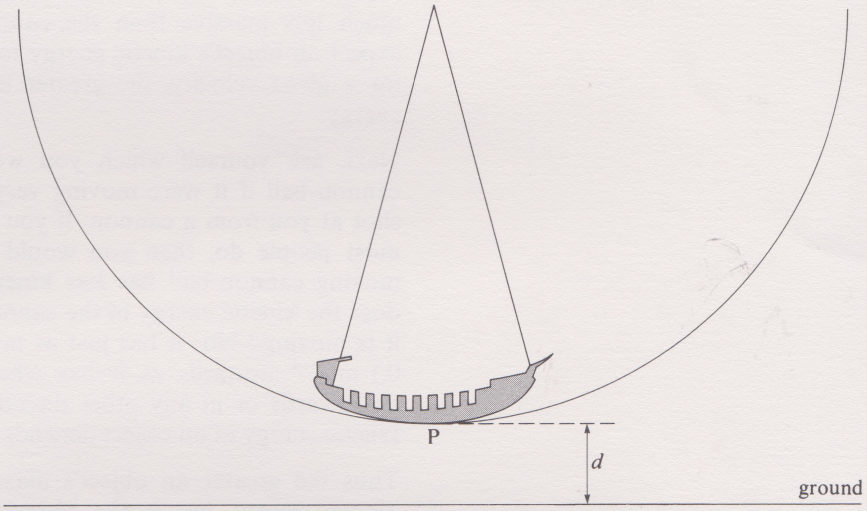
$$\Delta E_g = mg\ \Delta h$$

where g is the magnitude of the acceleration due to gravity in that region. When the object falls through the vertical distance Δh, then the amount of energy ΔE_g is converted to other forms of energy.

SAQ 5 A tourist, of mass 80 kg, polishes off a bowl of strawberries, with cream and sugar, in a street-level restaurant near the Post Office Tower in London. Conscious of having consumed 300 kcal, and feeling rather uncomfortable, he decides to 'work it off' by walking up the stairs of the Tower—a vertical distance of 170 m. Calculate how many kilocalories he works off in climbing the stairs once, assuming that the kilocalories are converted—through biochemical processes in his muscles and the rest of his body—entirely to gravitational energy. Do you think that this assumption is reasonable? (Take 1 kcal $= 4.2 \times 10^3$ J and $g = 10\ \text{m s}^{-2}$.)



(a) The gravitational energy of the swingboat is $mg(d+\Delta h)$ with respect to the ground, and $mg\Delta h$ with respect to point P.



(b) The gravitational energy of the swingboat is mgd with respect to the ground, and 0 with respect to point P.

FIGURE 9 Gravitational energy of a swingboat.

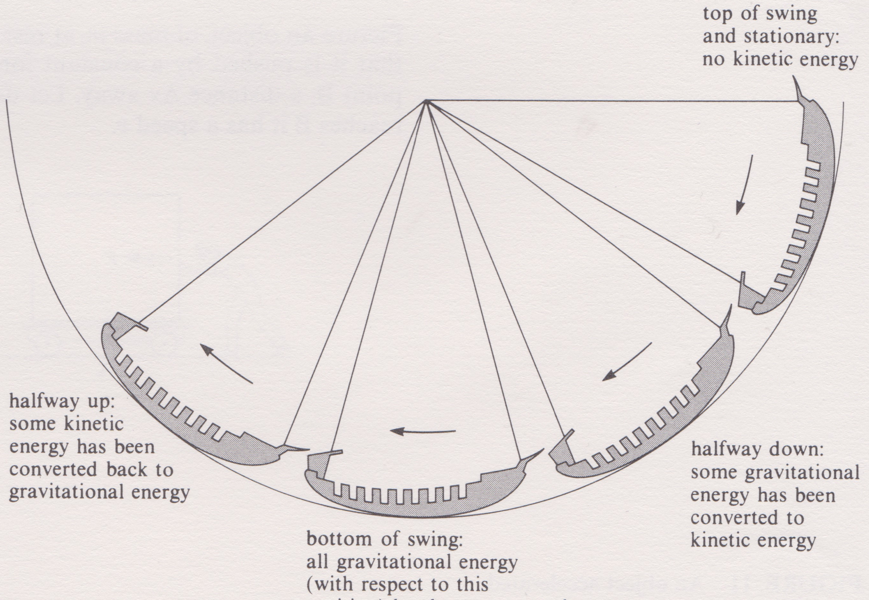


FIGURE 10 Energy conversions for a swingboat.

6 KINETIC ENERGY

In the example of the fairground swingboat shown in the TV programme and in Figures 9 and 10, there is a continuous interconversion between gravitational and kinetic energy (Figure 10). You know how to calculate the change in gravitational energy of the swingboat as it moves between any two positions. In this Section we will see how to work out its kinetic energy.

6.1 ON WHAT DOES THE KINETIC ENERGY OF AN OBJECT DEPEND?

Up to now, we've simply described kinetic energy as 'energy of motion', but what aspect of the motion actually determines the object's kinetic energy—its velocity, speed, acceleration or what? Is the kinetic energy dependent on the nature of the object, its mass or its density?

To make a start at answering these questions, ask yourself which you think has more energy, a cannon-ball moving horizontally at 20 m s^{-1} or a pea, shot from a pea shooter, moving at the same velocity. You know that it would be much easier for you to withstand the impact of the pea, since it is much less massive than the cannon-ball. It is, therefore, reasonable to expect an object's kinetic energy to depend on its *mass* in such a way that, for a given velocity, the greater the object's mass, the greater its kinetic energy.

Next, ask yourself which you would mind most—being struck by the cannon-ball if it were moving very slowly, say at 0.1 m s^{-1}, or if it were shot at you from a cannon. If you care as much about self-preservation as most people do, then you would certainly prefer the former. The slow-moving cannon-ball has less kinetic energy than a fast-moving one. But does the kinetic energy of the cannon-ball depend on the *direction* in which it is moving? No; it has just as much kinetic energy when it is moving at 0.1 m s^{-1} upwards as it has when it is moving at 0.1 m s^{-1} sideways, downwards or in any other direction for that matter. In other words, the kinetic energy of an object depends on its *speed* rather than on its velocity.

Thus the greater an object's mass m and speed v, the larger will be its kinetic energy, but is the energy proportional to $m \times v$, or $m^2 \times v$, or $m \times v^2$, or to some other combination of these quantities? Once again, we shall use the law of conservation of energy to help us find the answer.

6.2 A FORMULA FOR KINETIC ENERGY

Picture an object, of mass m, at rest on the ground at point A. Now suppose that it is pushed by a constant force of magnitude F (Figure 11) along to point B, a distance Δx away. Let us say that when, after time Δt, the object reaches B it has a speed v.

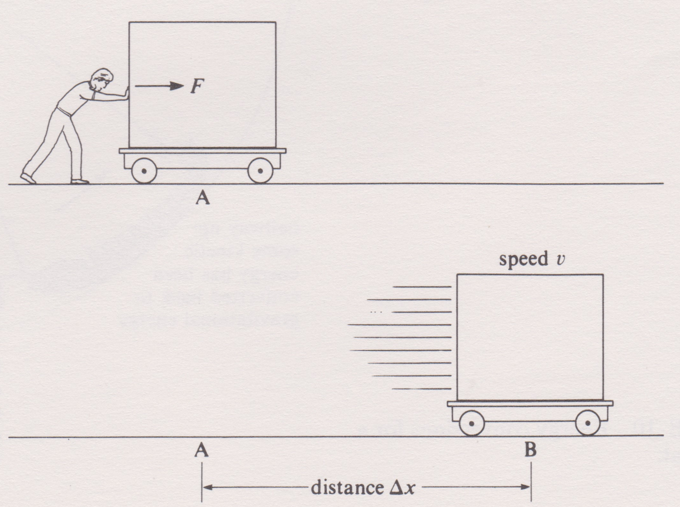


FIGURE 11 An object accelerated from A by a constant force of magnitude F covers the distance Δx to reach B after a time t with speed v.

As this is a thought experiment, we can assume there is no friction between the object and the ground or between the object and the atmosphere around it, so that all of the energy transferred to the object is converted into kinetic energy. In this 'ideal' case, the law of conservation of energy says that the energy supplied to the object should be exactly equal to its kinetic energy. We know the magnitude of the constant force acting on the object and the distance that the object has travelled, therefore we can calculate the energy that must have been transferred to the object—that is, how much energy has been converted into the kinetic energy of the object.

The energy transferred is the product of the magnitude F of the force and the distance travelled Δx (all quantities being expressed in SI units):

$$\Delta E = F\,\Delta x \tag{3}$$*

From Newton's second law (Unit 3), we know that F is related to the magnitude of the object's acceleration a by the equation

$$F = ma$$

The magnitude of the acceleration is given by the magnitude of the change in speed Δv divided by the time Δt taken for the change to take place:

$$a = \Delta v/\Delta t$$

Therefore

$$F = m\,\Delta v/\Delta t$$

and substituting back into Equation 3 we get

$$\Delta E = (m\,\Delta v/\Delta t) \times \Delta x \tag{6}$$

Is there some way of eliminating the quantities Δx and Δt from our expression for ΔE? Well, in Unit 3 you saw that the distance travelled by an object is equal to its average speed multiplied by the time it takes to complete the journey. In this case, the object's speed increases uniformly from zero to v, so its average speed is $v/2$. Now, because the object starts from rest, its overall change in speed, Δv, is just $(v - 0)$, or v. So we can say that its average speed is $\Delta v/2$. Consequently, the distance Δx that it travels in time Δt is $(\Delta v/2) \times \Delta t$. Substitution of this expression for Δx into Equation 6 gives

$$\Delta E = \frac{m\,\Delta v}{\Delta t} \times \frac{\Delta v}{2} \times \Delta t = \frac{1}{2}\,m(\Delta v)^2$$

When the object reaches B, all the energy transferred to it has been converted into kinetic energy, so from now on we shall denote the energy the object has acquired as E_k. As we have seen, in this particular case $\Delta v = v$, so we can write

$$\boxed{E_k = \frac{1}{2}\,mv^2} \tag{7}$$

This is a beautifully simple expression for the kinetic energy of a moving object, which (as suggested in Section 6.1) depends only on the mass and speed of the object. Note though, that in deriving it we considered only *translational* motion, that is motion in which all points within the moving object follow parallel paths. However, this isn't the only possible type of motion: objects can also *rotate*. There is of course a kinetic energy associated with rotational motion, but the derivation of an expression for that form of energy is beyond the scope of this Unit. For present purposes, it is enough to note that Equation 7 gives the total kinetic energy of a moving object that is not rotating (for example, a person sliding down a ski-slope), but gives only part of the kinetic energy of a rolling object (such as a football kicked along the ground).

In deriving Equation 7, what we actually worked out was the *change* in energy when the object accelerated from rest to a speed v. When we say that the kinetic energy of an object travelling at speed v is $\frac{1}{2}mv^2$, we really mean that this amount of energy must be transferred to the object for it to reach

speed v starting from rest. The same amount of energy will, of course, be converted to other forms if the object is brought to rest from an initial speed v.

ITQ 7 Show that Equation 7 is dimensionally correct (i.e. that the dimensions of mass × (speed)^2 are those of energy).

Notice that because the speed appears as a squared term in Equation 7, small changes in the speed would have a greater effect on an object's kinetic energy than would small changes in its mass.

□ If the speed of an object doubles, what happens to its kinetic energy?

■ The kinetic energy quadruples. For a given mass m travelling at speed v_1,

$$E_{k_1} = \frac{1}{2} m v_1{}^2$$

For the same mass travelling at speed $2v_1$,

$$E_{k_2} = \frac{1}{2} m(2v_1)^2 = \frac{1}{2} m \, 4v_1{}^2 = 2mv_1{}^2 = 4E_{k_1}$$

ITQ 8 A large saloon car has a mass of 1 050 kg. Calculate its kinetic energy at a speed of 80 km h^{-1} (50 m.p.h.). Enter your result on Table 1.

6.3 CONVERSION OF GRAVITATIONAL ENERGY INTO KINETIC ENERGY

We are now in a position to analyse more fully the energy conversions that take place in the swingboat. At the top of its swing (points M and N in Figure 12), it has maximum gravitational energy. At the bottom of its arc of swing (point P), it has minimum gravitational energy, and since the decrease in gravitational energy between M and P is, in the 'ideal' case, equal to the increase in kinetic energy, the kinetic energy must be a maximum at P. This kinetic energy is progressively re-converted to gravitational energy as the swingboat rises again from P until, at N, it has all been converted to gravitational energy. Thus, at point N, the kinetic energy is momentarily zero. Equation 7 shows that the speed must therefore also be zero (since, clearly, the mass is not zero). The energy argument proves that any object projected upwards stops momentarily at the top of its trajectory before falling back towards the Earth.

If we assume ideal behaviour for the swingboat, i.e. we ignore complications such as friction in the supports and air resistance, then it is quite easy to find an expression for its maximum speed. Yet again, we invoke the law of conservation of energy.

In the notation of Figure 12, at point M (or N), the swingboat has gravitational energy $mg \, \Delta h$ with respect to the point P. It will be moving with maximum speed v_{max} as it passes through point P, where all the gravitational energy has been converted to kinetic energy. Therefore,

$$\frac{1}{2} m \, (v_{max})^2 = mg \, \Delta h$$

Dividing both sides by m and then multiplying both sides by two gives

$$(v_{max})^2 = 2g \, \Delta h$$

and hence

$$v_{max} = \sqrt{(2g \, \Delta h)} \tag{8}$$

Equation 8 applies not just to the swingboat, but to any situation in which there is a complete conversion of gravitational energy to kinetic energy. Such a situation arises, for example, whenever an object is dropped from rest (provided that the effect of air resistance is assumed to be negligible).

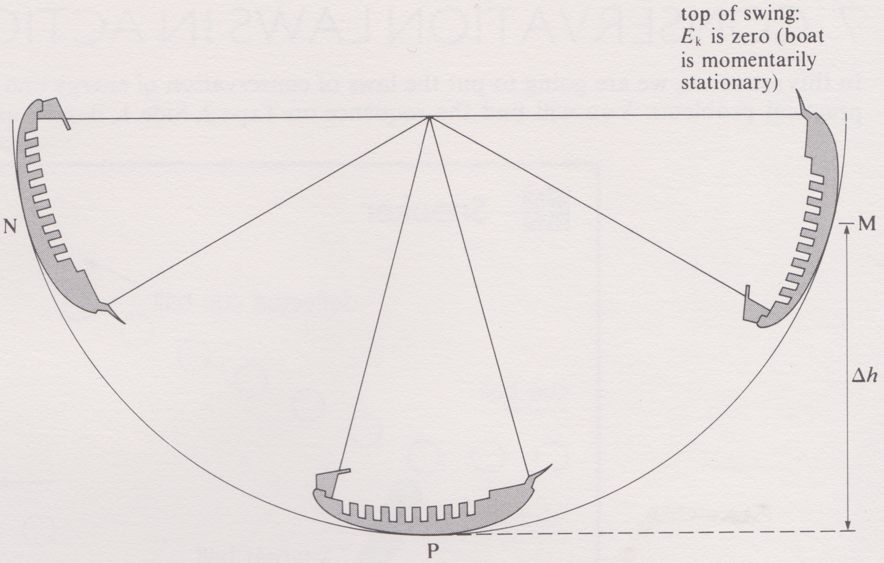


FIGURE 12 In a swingboat there is a continuous interconversion between gravitational and kinetic energy.

Equation 8 shows that in the case of an object falling through a given distance, the speed the object attains does not depend at all on its mass: if a lorry were to fall off the edge of a cliff, it would be moving no more quickly when it reached the shore below than a pebble dropped from the same height. You shouldn't be surprised by this result, as you already know from Unit 3 that the gravitational *acceleration* of an object is independent of its mass because of the dependence of the gravitational *force* on the mass of the falling object. It is comforting to note, though, that the approach using the law of conservation of energy gives the same result as we obtained in Unit 3.

SUMMARY OF SECTION 6

The kinetic energy of a moving object depends on both its mass and its speed. An object of mass m moving with speed v has an amount of kinetic energy, E_k, given by $\frac{1}{2}mv^2$.

SAQ 6 (a) A fielder throws a cricket ball of mass 0.15 kg towards the stumps. When the wicket-keeper catches the ball, it is moving at a speed of 20 m s^{-1}. Assuming the wicket-keeper stops it cleanly, how much energy is absorbed?

(b) If instead of aiming for the stumps the fielder were to throw the ball vertically upwards at a speed of 10 m s^{-1}, what height above the fielder's hand would it reach? (Assume that air resistance is negligible, and take $g = 10$ m s^{-2}.)

SAQ 7 In the sport of ski-jumping, the skiers start from rest at the top of a ramp (Figure 13). If the vertical drop on the ramp is 50 m, estimate the speed at which the skiers launch themselves from the end of the ramp. What assumptions have you made in arriving at an answer?

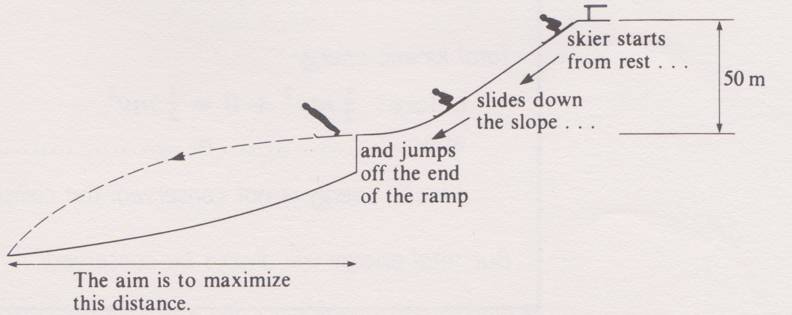
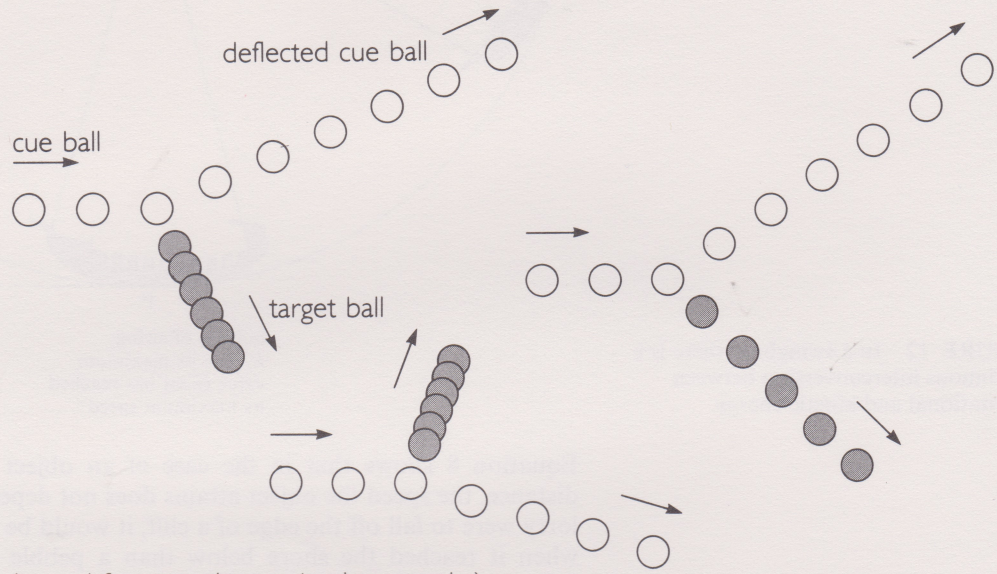


FIGURE 13 Ski-jumping.

7 CONSERVATION LAWS IN ACTION (AV SEQUENCE)

In this sequence, we are going to put the laws of conservation of energy and momentum to work in solving some practical problems. You will find the sequence on Tape 2, Side 1, Band 3 and Side 2, Band 1.

1 Snooker

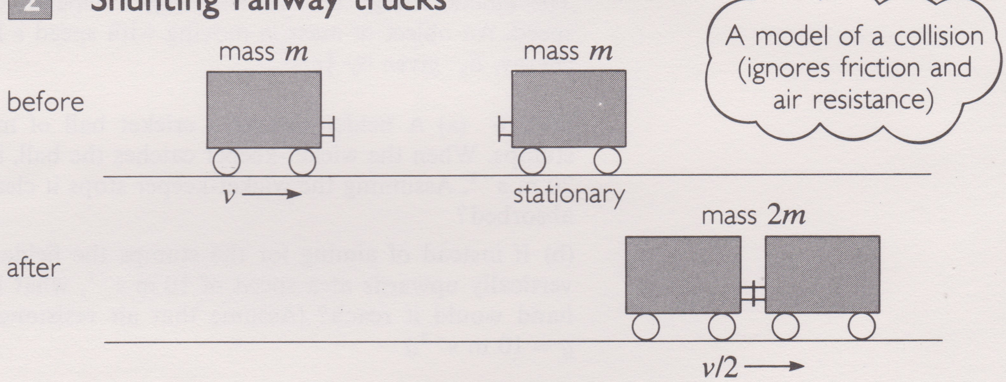


(traced from stroboscopic photographs)

The aim of this sequence is to analyse collisions using

- the law of conservation of energy
- the law of conservation of momentum

2 Shunting railway trucks



Total momentum

before: magnitude mv (from left to right)
after: magnitude $2m(v/2) = mv$ (from left to right)

Momentum is conserved.

Total kinetic energy

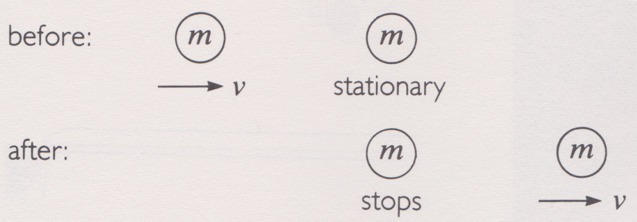
before: $\frac{1}{2}mv^2 + 0 = \frac{1}{2}mv^2$
after:.................. = ...

Kinetic energy is not conserved: the collision is inelastic.

But total energy will always be conserved!

3 More snooker

Another model (ignores friction and rotation of the balls)



Total momentum

before: ....

after: ....

Is momentum conserved? ....

Total kinetic energy

before: ....

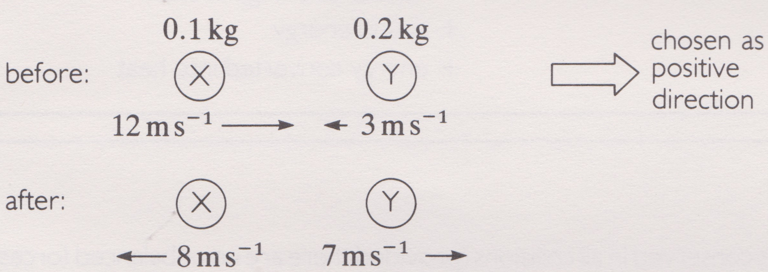
after: ....

Is kinetic energy conserved? ....

The collision is elastic.

4 A worked example

Same model as in Frame 3



before: $\frac{1}{2}(0.1\,\mathrm{kg}) \times (12\,\mathrm{m\,s^{-1}})^2 + \frac{1}{2}(0.2\,\mathrm{kg}) \times (-3\,\mathrm{m\,s^{-1}})^2 = 8.1\,\mathrm{J}$

after: $\frac{1}{2}(0.1\,\mathrm{kg}) \times (-8\,\mathrm{m\,s^{-1}})^2 + \frac{1}{2}(0.2\,\mathrm{kg}) \times (7\,\mathrm{m\,s^{-1}})^2 = 8.1\,\mathrm{J}$

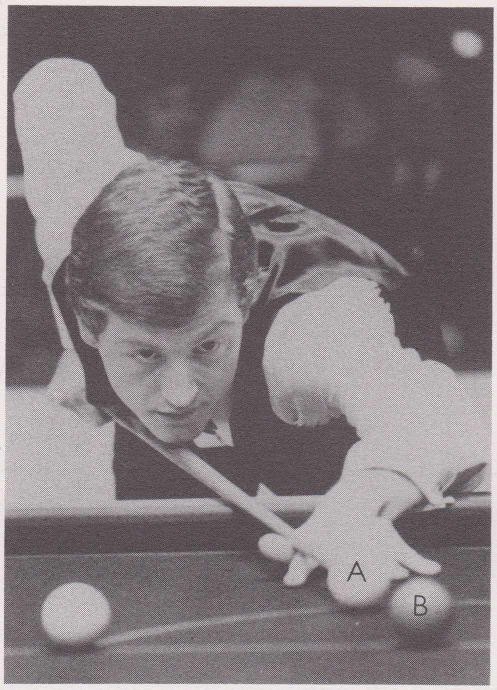
The collision is elastic.

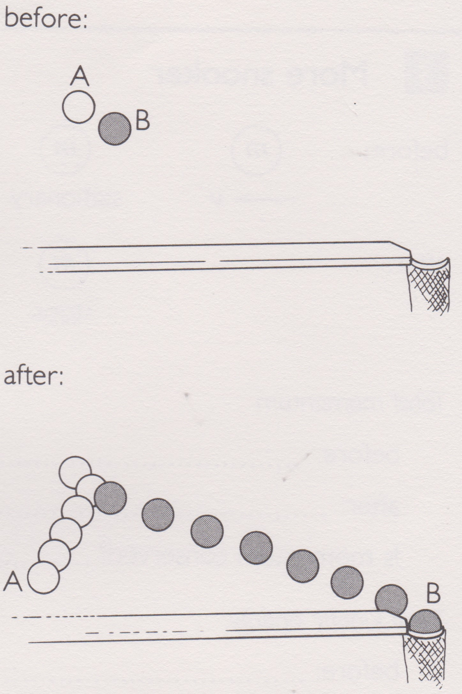
before: ....

after: ....

Momentum is conserved.

5 Real snooker





Gravitational energy is constant.

Before collision:		After collision:
kinetic energy of ball A + rotational energy of ball A	=	kinetic energy of ball A + kinetic energy of ball B + rotational energy of ball A + rotational energy of ball B + sound energy + energy converted into heat

6 Summary

- Total momentum is conserved in all collisions (provided there are no unbalanced forces).
- Total energy is conserved in all collisions (as in every physical system).
- Kinetic energy is conserved only in *elastic* collisions.

Answer to exercise in Frame 4

before: magnitude of total momentum (left to right)

$$\{(0.1 \times 12) + (0.2 \times [-3])\}\ \mathrm{kg\,m\,s^{-1}} = +0.6\ \mathrm{kg\,m\,s^{-1}}$$

after: magnitude of total momentum (left to right)

$$\{(0.1 \times [-8]) + (0.2 \times 7)\}\ \mathrm{kg\,m\,s^{-1}} = +0.6\ \mathrm{kg\,m\,s^{-1}}$$

KELVIN

TEMPERATURE

8 INTERNAL ENERGY

8.1 INTRODUCTION

In the ideal case discussed so far, once the swingboat is set in motion, it continues swinging for ever, converting gravitational energy into kinetic energy and back again. Of course we know that this doesn't happen in practice. Electrical energy must be continuously supplied to keep the swingboat in motion. If the power were turned off, the swingboat would slow down, rise less on each successive oscillation, and eventually come to rest. What then would have happened to its kinetic energy?

You could get a clue about the answer to this question by monitoring temperature changes in the system as the swingboat was brought to rest by the application of the brakes; you would find that the brakes got hot. In accordance with the law of conservation of energy, the apparently 'lost' kinetic energy hasn't been lost at all; at least part of it has been used to heat up the brakes—in other words, it has been converted into internal energy of the brakes. However, the easy quantity to measure directly is not the heat input to the brakes, nor their increase in internal energy, but the temperature rise. So how much does the temperature of an object increase when a given amount of energy is transferred to it? To answer this question we first need to explore in a little more detail the connection between temperature and heat transfer.

8.2 HEAT AND TEMPERATURE

The concept of **temperature** is a familiar one—it means the 'degree of hotness' of something. Cool water and hot water feel different to the touch, and one of the ways in which we describe this difference is by saying that they have different temperatures. When water just starts to freeze and to form ice (at a particular 'standard' atmospheric pressure), its temperature is defined as 0 °C (said as 'zero degrees Celsius or centigrade'); when it boils and forms steam (at the same 'standard' atmospheric pressure), its temperature is defined as 100 °C. This is how thermometers are calibrated—they are made so that they read 0 °C when immersed in an ice–water mixture and 100 °C when immersed in boiling water. The Celsius temperature scale (named after an 18th-century Swedish scientist, Anders Celsius, who first devised a form of this scale) is shown on the left of Figure 14. The calibration points of 0 °C and 100 °C are marked, together with a few other familiar temperatures for comparison.

Until about 1980, weather forecasters in the UK gave temperatures not in degrees Celsius, but only in degrees Fahrenheit. On the Fahrenheit scale, water freezes at 32 °F and boils at 212 °F. Many cookery books give oven temperatures in degrees Fahrenheit. Nowadays, use of the Fahrenheit scale is mainly confined to these two situations, but as it is still widely recognized, it has been included in Figure 14 for the sake of completeness.

When working in SI units, scientists use yet another scale of temperature, the **Kelvin** scale, named after a 19th-century physicist, Lord Kelvin, who did a great deal of pioneering work on heat engines. The Kelvin scale is also shown on Figure 14. As you can see by comparing the middle and right-hand scales in the Figure, a temperature rise of 1 kelvin* is the same as a rise of 1 degree Celsius but, on the Kelvin scale, water at standard atmospheric pressure freezes at 273.15 K and boils at 373.15 K.

Conversion of a temperature from the Celsius scale to the Kelvin scale is therefore quite straightforward:

$$\text{temperature in kelvin} = \text{temperature in degrees Celsius} + 273.15 \qquad (9)$$

* Note that by convention there is *no* little raised circle before the letter in the abbreviation for the SI unit of temperature. Thus we write 300 K and say 'three hundred kelvin', not 'three hundred degrees Kelvin'.

SPECIFIC HEAT

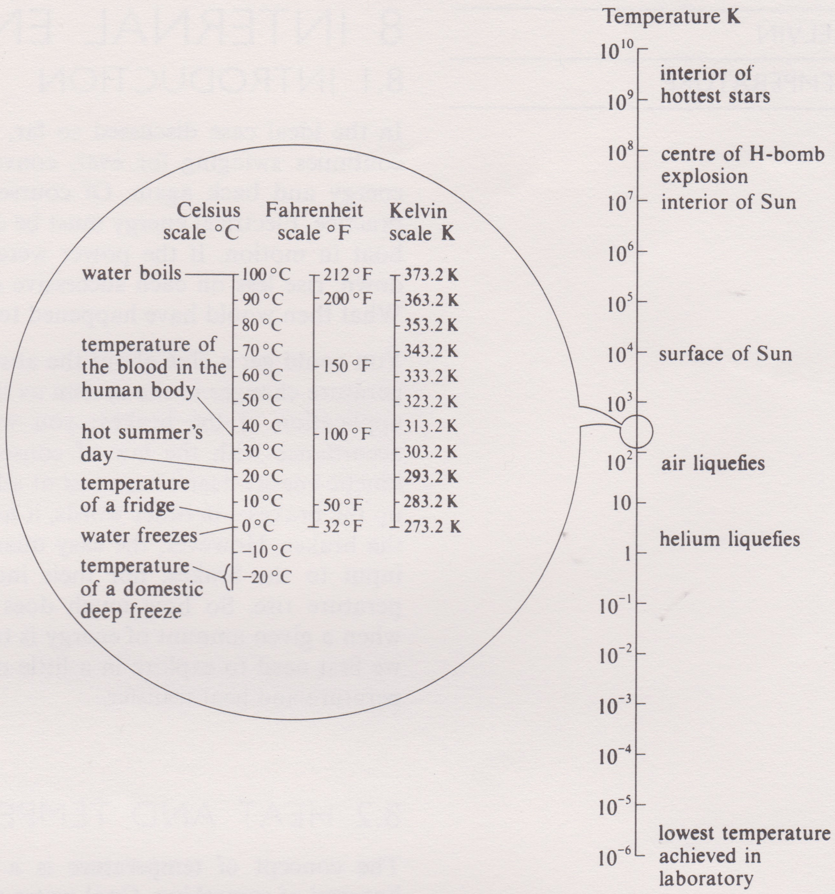


FIGURE 14 Temperature scales. (The right-hand scale is logarithmic.)

☐ Carbon dioxide gas freezes (forming so-called 'dry-ice') at 216.6 K. What is this temperature in degrees Celsius?

■ Rearranging Equation 9, and working to the number of significant figures given in the question,

$$\text{temperature in degrees Celsius} = 216.6 - 273.2 = -56.6$$

The freezing point of carbon dioxide is thus -56.6 °C.

The reasons for scientists often using the Kelvin scale, rather than the Celsius scale, are beyond the scope of this Course, but they can be summarized by saying that 0 K (called 'absolute zero') is the lowest temperature that any object can theoretically approach. There is actually a law that says this temperature is never reached in practice, but at the time of writing (1988) physicists have cooled matter to just 1 μK (i.e. 10^{-6} K) above absolute zero! The Kelvin scale is also intimately tied in with the behaviour of matter at the atomic level. We shall return to this aspect of temperature in Section 8.4.

Having got some feeling for what is meant by temperature, let us return to heat and internal energy. How are these related to temperature? You can begin to answer this question yourself by doing another thought experiment.

Imagine boiling some water in two large pans on a gas or electric cooker (Figure 15). If you were to adjust the controls of the cooker so that energy was supplied to both pans at a constant rate, you would expect it to take much longer to boil a gallon of water than to boil a pint (if both volumes had the same temperature initially). In other words, a smaller amount of chemical or electrical energy is transferred as heat and ultimately converted into internal energy of the water when a pint of water is boiled than when a gallon of water is boiled, *even though the final temperature of the water is the same* (100 °C) in both cases. Clearly, heat transfer and temperature change are not equivalent.

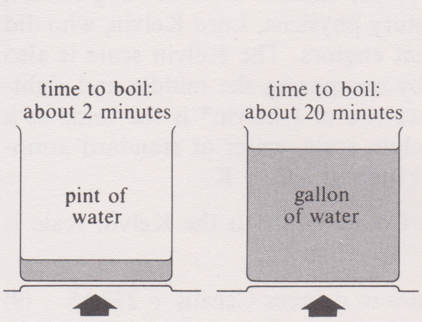


FIGURE 15 It takes more energy to boil a gallon of water than to boil a pint.

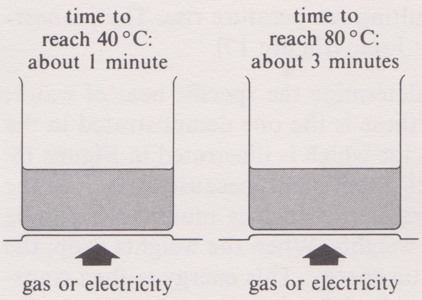


FIGURE 16 It takes more energy to heat water from room temperature to 80 °C than to heat the same amount of water from room temperature to 40 °C.

Yet there *is* a connection between these two quantities, as another thought experiment can quickly demonstrate. Suppose that the pans were now filled with the same amount of water (Figure 16), and again heated at the same rate. Obviously it would take longer to heat one panful to 80 °C than it would take to heat the other to 40 °C from the same starting temperature. The higher the temperature to which an object is heated, the more energy must have been transferred to it, so the greater must be its internal energy.

8.3 A FORMULA FOR HEAT TRANSFER

The thought experiment we have just discussed showed that the internal energy of the water increased as its temperature increased. Further quantitative experiments demonstrate that in fact the temperature rise ΔT of an object is directly proportional to the amount of heat ΔQ transferred to it:

$$\Delta Q \propto \Delta T \tag{10}$$

The thought experiment illustrated in Figure 15 also showed that more energy must be transferred to heat a large quantity of water through a particular temperature interval than to heat a smaller quantity of water through the same temperature interval. In fact, in a classic experiment, Joule proved that if the *mass* of the water were doubled, then double the amount of energy had to be transferred to raise its temperature by the same number of degrees: the heat transfer, ΔQ, required to produce a given temperature change in an object is directly proportional to the mass m of that object:

$$\Delta Q \propto m \tag{11}$$

Proportionalities (10) and (11) can be combined into one:

$$\Delta Q \propto m \times \Delta T \tag{12}$$

To make Proportionality 12 into an equation, we have to find the constant of proportionality. At this stage we have to ask whether this is a universal constant, i.e. the same for all substances, under all conditions. To answer this, imagine replacing the water in the experiments of Figures 15 and 16 with another liquid—treacle, say, or alcohol. If you were, by a transfer of heat, to supply a certain amount of energy to the same masses of water and of some other liquid, would you expect their temperatures to increase by the same amounts? There is no reason to suppose that they would. The constant of proportionality is thus different for each substance: it is known as the **specific heat** (or, in full, specific heat capacity) of the substance and is usually denoted by the letter c. Proportionality 12 can therefore be rewritten in the form of an equation

$$\boxed{\Delta Q = mc\,\Delta T} \tag{13}$$

□ What are the SI units of specific heat?

■ The unit of ΔQ (i.e. energy transfer) is the joule, the unit of ΔT is the kelvin and the unit of mass is the kilogram. The units of both sides of Equation 13 must be the same, i.e.

$$\text{J} = \text{kg} \times (\text{units of } c) \times \text{K}$$

A rearrangement of this gives

$$(\text{units of } c) = \text{J kg}^{-1}\,\text{K}^{-1}$$

A similar rearrangement of Equation 13 provides the basis for the determination of the specific heat of any given substance:

$$c = \Delta Q/(m\,\Delta T)$$

To measure the specific heat of a substance it is therefore necessary to take a known mass of the substance, heat it so as to transfer to it a known

FIGURE 17 James Joule (1818–89). In a time marked by many remarkable scientific discoveries and many ingenious and accurate experiments, Joule's achievements nevertheless tower above those of most of his contemporaries. Joule was the owner of a Manchester brewery, who pursued his scientific studies as a hobby, yet his skill in designing experiments to give precise and accurate information was unrivalled.

amount of energy, and measure the resulting temperature rise. The pioneering work in this field was carried out by Joule (Figure 17).

Joule designed several experiments to determine the specific heat of water; the most famous and most accurate of these is the one demonstrated in the TV programme 'Energy', the apparatus for which is illustrated in Figure 18. It is usually known as the 'paddle-wheel' experiment, because in essence the apparatus consists of a container of water in which is mounted a paddle wheel that is driven by a pair of falling weights. When the weights drop, the paddle wheel turns, i.e. it acquires kinetic energy. This energy is then transferred to the water, so heating it up. Joule's aim was to measure the resulting increase in the temperature of the water.

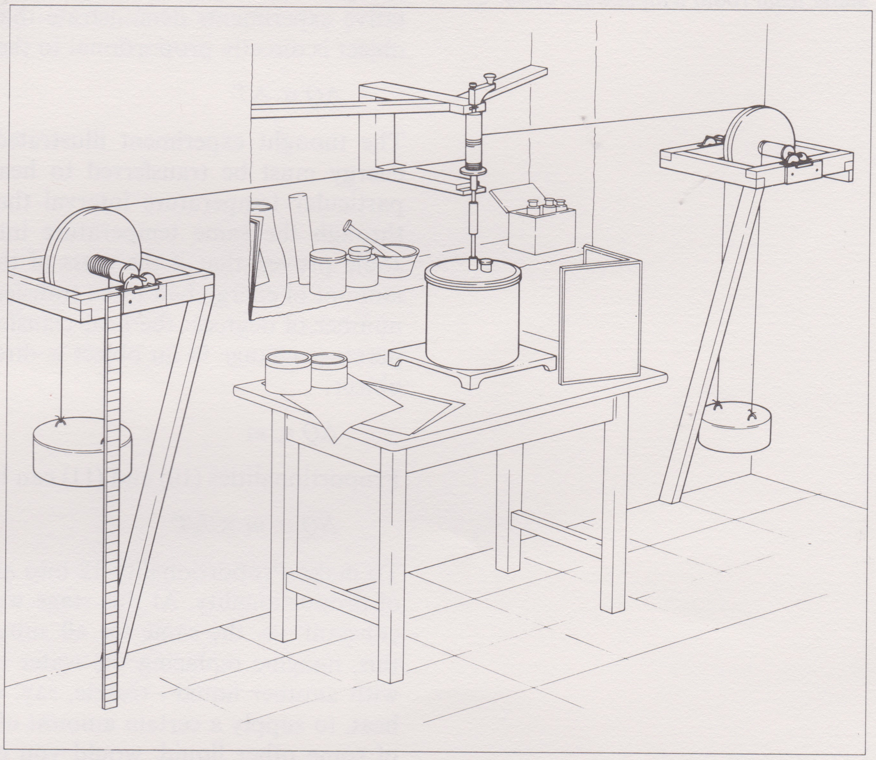


FIGURE 18 Joule's apparatus.

The basic apparatus and operating principle are quite easy to describe, but in practice it is extremely difficult to obtain an accurate and precise result from such an experiment. The main problem lies in ensuring that as much as possible of the kinetic energy of the falling weights is converted to internal energy of the *water* (i.e. that no energy 'leaks away' through the walls of the container). Joule was particularly skilful at minimizing energy losses of this type and at quantifying those that were unavoidable.

As far as possible, he tried to carry out the experiments in an environment with a uniform temperature, and the cellar of his brewery proved extremely useful in this respect! He also realized that the greater the temperature difference between the apparatus and the surrounding air, the more quickly energy leaked away, so he tried to use only a very small temperature rise in the water. Of course this had the disadvantage that he was trying to measure very small temperature differences and he had to make special thermometers to do this. In his most precise experiments, Joule was fairly confident of measuring temperatures to within 1/200 of a degree Fahrenheit—quite an achievement in the mid 1800s! The result he finally obtained for the specific heat of water was remarkably close to the currently accepted value. You can work through Joule's reasoning for yourself in the following ITQ.

ITQ 9 In the version of Joule's experiment shown in the TV programme, the paddle wheel was turned by the repeated fall of two weights, each of mass 13.2 kg, through a distance of 1.02 m. Each weight was wound up and

TABLE 2 Specific heats of a few common substances.

Substance	Specific heat/ $J\ kg^{-1}\ K^{-1}$
water	4.2×10^3
paraffin	2.1×10^3
air	9.9×10^2
aluminium	9.0×10^2
copper	3.8×10^2

Note Strictly speaking, the specific heat of a substance depends on the conditions (of pressure and volume) under which it is measured. This complication is ignored in this Unit.

allowed to fall twenty times. The mass of water in the container was 3.20 kg, and the increase in temperature of the water was measured as 0.390 K.

(a) What was the total kinetic energy transferred from the falling weights? (Take $g = 9.8\ m\ s^{-2}$)

(b) Assuming that all the kinetic energy of the weights is converted to heat and that this heat is all absorbed by the water, what, according to these measurements, is the specific heat of water?

The experiment described in ITQ 9 is a somewhat simplified version of what Joule actually did: in his own experiments, Joule introduced many refinements in technique and a number of corrections to the data. Nevertheless, by working through the question, you should have gained some idea of the difficulties Joule faced and the size of the temperature changes he measured. The value of the specific heat of water is 4 186.8 $J\ kg^{-1}\ K^{-1}$. It is salutary to note that in 1878 Joule obtained what he considered to be his most accurate value: 4 172 $J\ kg^{-1}\ K^{-1}$, which is within 0.4% of the present-day one.

The specific heats of a few other common substances are given in Table 2. Notice how large the specific heat of water is compared with those of the other substances.

□ Would it take more or less energy to warm a piece of copper from room temperature to 100 °C than to warm the *same* mass of aluminium through the same temperature interval?

■ Equation 12 shows that the energy required is directly proportional to the specific heat (since in this case m and ΔT are constant). The specific heat of copper is less than that of aluminium (Table 2), so it takes less energy to warm the mass of copper. This means, for example, that a copper saucepan would take a shorter time to warm up to a given temperature than an aluminium one of the same mass, provided that the same amount of energy were used to do the heating.

8.4 INTERNAL ENERGY AND TEMPERATURE

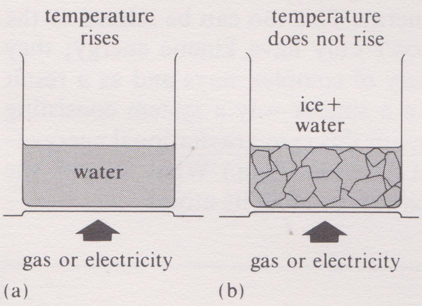


FIGURE 19 Heating (a) water and (b) an ice–water mixture.

If you put a pan of water on a working ring of a gas or electric cooker (Figure 19a), then you would not be in any doubt about what was happening to the chemical or electrical energy you were 'using': it would be converted into internal energy in the water, which would warm up. Now imagine that, instead of being filled with water, the pan contained a mixture of ice cubes and water at 0 °C (Figure 19b). If you supplied energy at the same rate as before, you would find that, so long as there was ice in the pan, the temperature of the water in the pan would not rise. Why, when there is an energy *input* into the system, does the temperature of the water not change? Does this mean that there is no conversion into internal energy and, if so, where is the energy going?

The reason for there being no temperature change when an ice–water mixture is heated is quite straightforward: the energy supplied to the system is used to melt the ice, but the temperature of the ice is the same (0 °C) as that of the water resulting from the melting process. The substance undergoes a *change of phase* from solid to liquid and this requires energy. Why?

To answer this question it is necessary to have some understanding of the structure of matter. You will learn more about this later in the Course, but for the moment a few basic ideas will suffice.

The fact that all substances are made up of tiny particles called atoms has already been mentioned several times. These particles are far too small to be seen with even the most powerful optical microscopes, and therefore quite small amounts of matter contain huge numbers of atoms: a pint of water contains more than 10^{24} atoms! There are many types of atom and they can be bound together (to form combinations called molecules) in many ways.

The atoms in a substance are always in motion. To see this, you might like to do a simple experiment: gently drop a small blob of ink on to the surface of a still glass of water and leave the glass and its contents for an hour or so. You will find that after this time the ink has spread out uniformly through the water. Although once it has settled on the surface of the water the blob of ink as a whole has no energy of motion, each of the atoms within it has kinetic energy. Each atom is free to move through the boundary between the ink and the water, until the two liquids are inextricably mixed. Gases also consist of atoms that are in constant motion: that is why perfume, or cooking smells, quickly pervade a room. More complex experiments have to be devised in order to investigate the behaviour of atoms in solids, but such experiments confirm that in solids too the atoms are always in motion.

In all three phases of matter—solid, liquid and gas—the motion of the atoms is *random*, that is they do not all move at the same speed, nor in predictable directions. However, one aspect of the motion is completely predictable: for a given substance, the higher its temperature, the greater the average speed of its atoms. If you heat up, say, a sample of neon gas, thereby transferring energy to it, this energy is converted into kinetic energy of the neon atoms. *The temperature of the gas thus determines the average kinetic energy of its atoms.* In fact, for a substance in any phase

temperature of a substance in kelvin

$\propto$ average kinetic energy of the constituent atoms

This is an extremely important result, in that it ties the temperature of a substance, which is a *macroscopic* (i.e. large-scale) property of the sample as a whole, to the behaviour of the *microscopic* constituents of the substance. Notice that, according to this proportionality, at a temperature of 0 K atoms have zero kinetic energy—in other words they are stationary. Thus, on the basis of this relationship, one can visualize that as a substance is cooled, its atoms move, on average, more and more slowly, until at 0 K they stop moving altogether. It is then impossible to cool the substance any further. Zero kelvin (also called 'absolute zero') is said to be the lowest temperature that a substance can approach.

In transferring heat to our sample of neon gas, we not only raise its temperature, we also increase its internal energy. This too can be related to the behaviour of the gas atoms. Atoms don't only have kinetic energy; they attract and repel one another in a variety of complex ways and as a result possess a stored 'interaction energy'. (In a similar way a system consisting of an apple and the Earth stores energy—in this case gravitational energy—because of the gravitational attraction between them.) What we call the internal energy of a substance is the *total* energy of all its atoms.

internal energy of a substance

= total energy of its constituent atoms

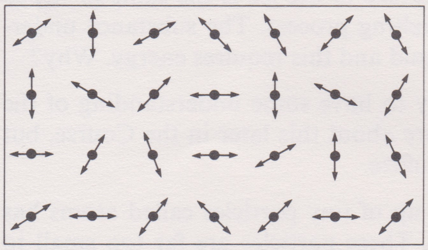


FIGURE 20 Atoms in a solid vibrate in random directions about fixed positions. (Note that this is a plan view; the vibrations actually occur in three dimensions.)

Let us now return to the question posed by the results of the experiment described in Figure 19: why is energy required to melt a solid, or to boil a liquid, even without changing its temperature? To answer this question, we have to consider in a little more detail the interactions between atoms.

In solids, the forces between the atoms are such that the atoms are bound in fixed positions about which they vibrate in random directions. Because the atoms in solids cannot just move away freely, solids are fairly rigid. Figure 20 is an illustration of atoms vibrating in a solid—for simplicity, only a very few atoms are shown. The arrows 'attached' to each of the atoms indicate the line along which it is vibrating at a particular instant. The arrows point in different directions to show that the direction of vibration is random, and will almost certainly be quite different at some other instant.

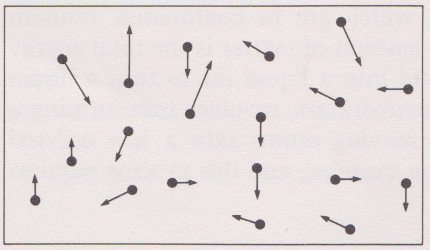


FIGURE 21 Atoms in a liquid do not move about fixed points.

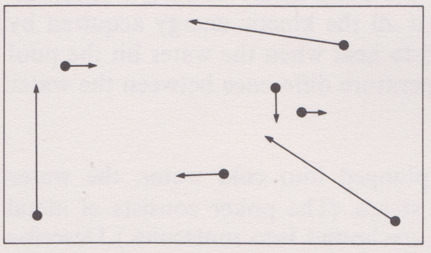


FIGURE 22 Atoms in a gas are, on average, further apart than those in a liquid and can move freely.

As the temperature of the solid is raised, the average kinetic energy of the atoms increases and they vibrate more vigorously. At the temperature at which the solid melts, the vibrations are so vigorous that they overcome the forces that bind the solid in its rigid shape and the solid melts into a liquid. In liquids, the atoms can travel around within the body of the liquid (Figure 21). Again, as the temperature is increased still further, and the forces between the atoms are reduced, the average kinetic energy of the atoms increases and they move more and more quickly. When the liquid boils, the atoms have sufficient energy to overcome the forces that attract them to their neighbours: they can escape from the body of the liquid into the gas above it. In the gas, the atoms not only move more quickly than in the liquid, they also travel around freely, frequently colliding and exchanging kinetic energy (Figure 22). If the temperature is further increased, the atoms, on average, travel faster still.

Thus, when you want to melt a block of ice, you must supply energy to the atoms in the ice to enable them to overcome the forces binding them into the ordered atomic arrangement typical of a solid. The total energy of the atoms in a given amount of water at 0 °C is greater than the total energy of the atoms in the same amount of ice at 0 °C (at the same pressure). In other words, the internal energy of a given mass of water at 0 °C is greater than the internal energy of the same mass of ice at 0 °C.

ITQ 10 Which of the following statements is/are true?

(a) The temperature of a liquid always rises when energy is supplied to it in the form of heat.

(b) The speed of an individual atom in a gas at a given instant is determined by the temperature of the gas.

(c) If the temperature of a substance increases, its internal energy necessarily increases.

(d) If the internal energy of a substance increases, its temperature necessarily increases.

There are two final points to note about heat and internal energy. The first is that we have equated the internal energy of a substance with the total energy of its constituent atoms. This total energy includes the interaction energy between atoms, which depends on the relative positions of the atoms. Therefore, like gravitational energy, interaction energy is not an absolute quantity. This means that it is not possible to determine an absolute value for the internal energy of a sample of matter: all we can measure are *changes* in internal energy. Secondly, even changes in internal energy are difficult to measure: when we raise the temperature of a system, the quantity we can determine experimentally (apart from the temperature rise) is the amount of heat transferred. However, this is not usually equivalent to the change in internal energy. If there is a change in phase, or even a simple expansion of the sample, the increase in internal energy will be smaller than the amount of energy transferred to it in the form of heat. Only in the very special case of a sample completely isolated from its surroundings and kept at constant volume is the change in internal energy equal to the amount of heat transferred.

SUMMARY OF SECTION 8

1 The amount of heat ΔQ required to change the temperature of an object of mass m and specific heat c by an amount ΔT (with no change of state) is

$$\Delta Q = mc\,\Delta T$$

2 The specific heat of a substance is the energy required to raise the temperature of one kilogram of the substance by one degree Celsius (or one kelvin). The SI units of specific heat are J kg^{-1} K^{-1}. (Note that J kg^{-1} K^{-1} and J kg^{-1} °C^{-1} are numerically equivalent.)

CHARGE

ELECTROSTATIC FORCE

COULOMB

COULOMB'S LAW

3 All matter is made up of atoms, which are in continuous, random motion. The internal energy of a given amount of matter is the total energy of its constituent atoms. To melt a solid into a liquid (or to turn a liquid into a gas), even without a change in temperature, involves transforming a more ordered arrangement of slower-moving atoms into a less ordered arrangement of faster-moving atoms (on average), and this process requires an input of energy.

SAQ 8 What facts would you need to know if you wanted to find the amount of energy required to bring a saucepan of milk to the boil?

SAQ 9 The waterfall shown in the TV programme is Pistyll Rhaeadr, which has an overall drop of 73.2 m. If all the kinetic energy acquired by the water during its fall were converted to heat when the water hit the pool at the bottom, what would be the temperature difference between the water at the top and that at the bottom?

SAQ 10 When a red-hot poker is plunged into cold water, the water warms up and some of it boils off as steam. (The poker consists of metal atoms; the atoms in water and steam are bound into molecules.) Describe what happens to the atoms in the poker and to the water molecules.

9 ELECTRICAL ENERGY

We have left until last what is in many ways the most familiar type of energy—electrical energy—which is transformed every time we switch on a light or start up a washing machine. However, before we can develop a quantitative expression for the amount of electrical energy transformed in various situations, it is necessary to take a step back to look at electric **charge** and electric current.

9.1 ELECTRIC CHARGE

In Section 2.5 and in Units 5–6, you saw that what we normally call electric current is actually a movement of charged particles or, more precisely, a flow of *electrons*. You will find out a great deal about electrons in Units 11–12, but for our present purposes we are only interested in their property of charge. So what *is* charge? How does one tell whether an object is charged? Is charge only of interest when it is flowing or are any effects associated with stationary charge?

Let us take the last question first. You can probably answer this yourself, especially if you replace the word 'stationary' with the similar term 'static'. We use 'anti-static' cloths to clean gramophone records because a charge tends to build up on records and this attracts dust from the atmosphere. You may have noticed that nylon clothes tend to attract other nylon garments; this is especially obvious when a bundle of dry clothing is lifted out of a tumble dryer. When taking off a nylon sweater you may hear crackles, and in a darkened room you may even see sparks. All these effects arise because gramophone records, dust particles, nylon fabric and hair can acquire charge, and because charged objects exert forces on other charged objects. A series of experiments with a variety of objects can be used to establish the following facts:

1 Any object can have one of two types of charge, or it can have no charge at all. There are two types of charge: positive and negative.

2 Charge is a property of matter. When an object is charged, it does not appear any different to when it is uncharged—you cannot see or hear the presence of charge and it has no shape or size. (A nylon sweater doesn't look any different if it is charged.) The only way in which you can tell that something is charged is to see whether it will interact with another charged object.

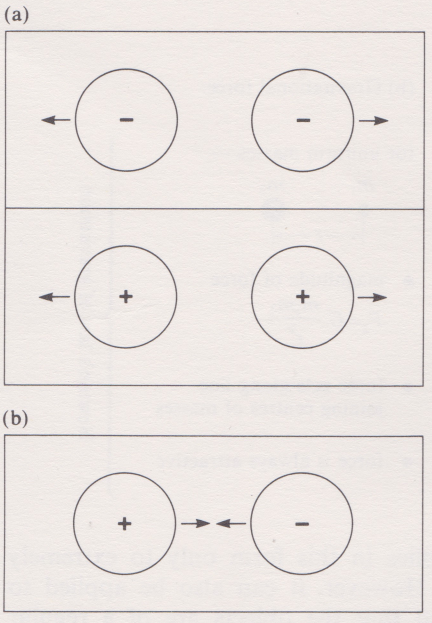


FIGURE 23 Electrostatic attraction between charged objects: (a) like charges repel; (b) unlike charges attract.

What laws describe the interaction of charges?

3 If two stationary objects are brought together and they are *both* positively or *both* negatively charged, then they always repel each other (Figure 23a). The force that pushes them apart is called an **electrostatic force**.

4 If two stationary objects have *opposite* charge (one positively charged, the other negatively charged), then they always attract each other (Figure 23b). The force that pulls them together is also known as an electrostatic force. Thus an electrostatic force can be either attractive or repulsive, according to whether it acts between like or unlike charges.

5 No electrostatic force acts on an object that is uncharged.

9.2 STATIONARY CHARGES AND ELECTROSTATIC FORCES

Having accepted that like charges repel and unlike charges attract, we might ask 'How *strongly* do charges repel and attract one another?' In fact, the magnitude of the force between a pair of charged objects depends on two factors: the amount of charge on each of the objects and the distance between the objects.

In SI units, amounts of charge are measured in **coulombs**, abbreviated to the capital letter C, and named after the 18th-century French scientist Charles de Coulomb who did pioneering work in this field. By everyday standards, a coulomb is a substantial amount of charge: an item of nylon clothing might have a charge of magnitude 10^{-5} C when it comes out of a tumble dryer (and that can be enough to cause sparks to fly!). Remember that charges have a sign as well as a value. Electrons, for example, are negatively charged: each electron carries a charge of approximately -1.602×10^{-19} C.

Coulomb found that the magnitude of the electrostatic force, F_{el}, between two point charges of magnitude Q_1 and Q_2 was directly proportional to both Q_1 and Q_2, i.e.

$$F_{el} \propto Q_1 \quad \text{and} \quad F_{el} \propto Q_2$$

These two proportionalities can be combined by writing

$$F_{el} \propto Q_1Q_2 \tag{14}$$

Coulomb also found that the greater the distance r between the point charges, the smaller the electrostatic force between them. In fact, he found that

$$F_{el} \propto \frac{1}{r^2} \tag{15}$$

Proportionalities (14) and (15) may be combined as

$$F_{el} \propto \frac{Q_1Q_2}{r^2}$$

or, in terms of an equation as

$$\boxed{F_{el} = A\,\frac{Q_1Q_2}{r^2}} \tag{16}$$

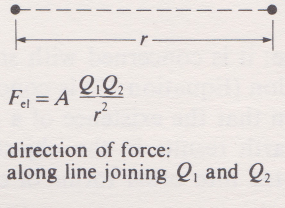


FIGURE 24 Coulomb's law.

where the constant of proportionality, A, is a universal constant whose value may be determined by experiment. The direction of the force is along the line joining the two charges: it is attractive in the case of unlike charges and repulsive in the case of like charges. This is known as **Coulomb's law** (Figure 24).

ITQ 11 In what SI units is the constant A in Equation 16 measured?

VOLTAGE (POTENTIAL) DIFFERENCE

VOLT

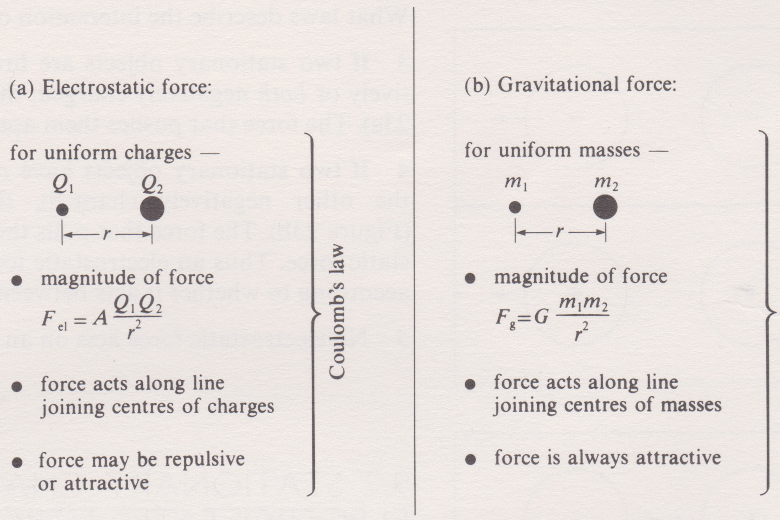


FIGURE 25 Electrostatic and gravitational forces.

Strictly speaking, Coulomb's law applies in this form only to extremely small, point-like, objects (Figure 24). However, it can also be applied to macroscopic charged objects provided that the objects are of a regular shape: the separation, r, between them is then taken to be the distance between their centres, as shown in Figure 25a. In many ways, this is reminiscent of the situation you encountered in Unit 3 when considering the *gravitational* force between large bodies such as the Earth and the Moon: the separation of the two bodies was also taken to be the distance between their centres (Figure 25b). Indeed, the form of Newton's law of gravitation, which gives the magnitude of the gravitational force F_g between two masses m_1 and m_2, separated by a distance r as

$$F_g = G\frac{m_1m_2}{r^2} \tag{17}$$

is very similar to the form of Coulomb's law (Equation 16). However, there are important differences between the gravitational force and the electrostatic force. For one thing, the gravitational force between objects always acts in the same way: it is always attractive. However, since charge comes in two varieties—positive and negative—the electrostatic force between objects can be either repulsive or attractive, depending on whether the objects have charges of the same sign or of opposite signs. The second difference between F_{el} and F_g arises because all macroscopic objects have mass, but not all objects are charged. Equation 16 shows that if $Q_1 = 0$ and/or $Q_2 = 0$, then $F_{el} = 0$. In other words, there is no electrostatic force between two objects if either (or both) of them is uncharged. On the other hand, there is always a gravitational attraction between any two objects. The similarities and differences between electrostatic and gravitational forces are summarized in Figure 25.

ITQ 12 Electrons each have a charge of approximately -1.6×10^{-19} C and a mass of approximately 9.1×10^{-31} kg. What are the electrostatic and gravitational forces between two electrons separated by a distance of 1.0×10^{-10} m? (This is the approximate separation of two electrons within an atom.) You may assume a value for the constant A of 8.99×10^9 N m^2 C^{-2}, and the value for G given on the back cover of these Units.

9.3 MOVING CHARGES AND ELECTRICAL ENERGY

Coulomb's law refers to an electro*static* force: it is concerned with *stationary* charges, just as Newton's law of gravitation (Equation 17) is concerned with stationary masses. We have already seen that the existence of a gravitational force between an object and the Earth results in the object possessing gravitational energy, which is converted into other forms of energy if the object falls.

An analogous situation obtains between two separated charges: an electrostatic force exists between them, so they possess electrical energy, and this energy can be transferred or converted when the charges move.

If the terminals of a battery are connected by metal wires, an electric current flows: negatively charged electrons flow through the wires from the negative terminal to the positive terminal. One way to explain why this happens is to say that the electrons are repelled by the negative terminal and are attracted by the positive terminal. Alternatively, we can use an energy argument, and say that the electrons flow to the positive terminal because their electrical energy is lower at that terminal. This is analogous to saying that an object will fall to the Earth when released, because the object's gravitational energy is thereby reduced.

The change in electrical energy when a charge moves from one position to another is determined by a quantity called the **voltage difference** (also known as the **potential difference**) between those two positions. The voltage difference ΔV is defined as the electrical energy difference per unit positive charge:

$$\text{voltage difference} = \frac{\text{electrical energy difference}}{\text{charge}}$$

or, in symbols:

$$\Delta V = \Delta E_{\text{el}}/Q \qquad (18)$$

The common unit of voltage difference is the **volt** (denoted by the letter V), which is defined such that the voltage difference between two places is exactly one volt if the transfer of one coulomb of positive charge between the two places requires an energy transfer of one joule. Thus

$$1 \text{ volt} = 1 \text{ joule per coulomb}$$

$$1\text{V} = 1 \text{ J C}^{-1}$$

Equation 18 can be rearranged to get an expression for the amount of electrical energy transferred by a positive charge Q moving through a voltage difference ΔV:

$$\boxed{\Delta E_{\text{el}} = Q\,\Delta V} \qquad (19)$$

□ Suppose that 250 coulombs of charge are transferred from the negative terminal of a 12-volt car battery via the starter motor to the positive terminal. What is the decrease in electrical energy of the electrons involved?

■ Applying Equation 19,

$$\begin{aligned}\Delta E_{\text{el}} &= 250 \text{ coulombs} \times 12 \text{ volts}\\ &= 250 \text{ C} \times 12 \text{ J C}^{-1}\\ &= 3\,000 \text{ J}\end{aligned}$$

This amount of electrical energy is converted into the kinetic energy of the starter motor and engine, and into internal energy.

ITQ 13 Given that the magnitude of the charge on the electron is 1.602×10^{-19} C, calculate the energy (in joules) that must be transferred to an electron if it is to be accelerated between two places that have a voltage difference of 1 V.

As mentioned in Section 4.2, the amount of energy calculated in ITQ 13 is called one electronvolt (abbreviated as 1 eV). The electronvolt is a unit of energy that is frequently used in discussions of atoms and sub-atomic particles, so you will come across it again later in the Course. As you will see, it is a much more convenient unit than the joule for some applications, simply because it is much smaller.

ELECTRIC CURRENT

AMPERE

POWER

WATT

9.4 CURRENT AND POWER

When you think about the operation of an electrical device, you probably don't consider how *many* electrons, or how *much* charge flows through it. You are far more likely to consider the *rate* at which charge flows through it—in other words the **electric current**. Formally, the electric current in a circuit is defined as the amount of charge transferred past a given point per unit time. Thus if Q coulombs of charge flow past a particular point at a constant rate in time t, the current (normally denoted by I) is given by the equation

$$I = Q/t \tag{20}$$

The SI unit of current is thus one of (charge/time), i.e. C s^{-1}. In honour of André-Marie Ampère, another French scientist of the 18th century, this unit is given the name of **ampere** (often shortened to amp) and denoted by the letter A:

$$1\ \mathrm{A} = 1\ \mathrm{C\ s^{-1}}$$

The electricity board supplies homes with charge; all that consumers have to do is to plug their gadgets into the mains supply and the charge flows down the connecting wires, making electrical energy available for conversion into other forms. The voltage of a consumer's mains supply is always the same, but different devices require charge to be delivered at different rates in order to operate them. The rate at which one form of energy can be converted into another is given the name **power**. Provided the energy is being converted at a constant rate,

$$\text{power} = \frac{\text{amount of energy converted}}{\text{time taken for the conversion}} \tag{21}$$

Although we most often think of power in connection with electrical energy and the 'power rating' of various electrical applicances, Equation 21 is quite general and can be used in any situation in which energy is transferred or transformed at a constant rate.

The SI unit of power is therefore one of (energy)/(time), i.e. J s^{-1}. This unit too is given a special name, the **watt** (after the Scottish engineer James Watt, who played a major role in the development of the steam engine), and is denoted by the letter W.

$$1\ \mathrm{W} = 1\ \mathrm{J\ s^{-1}} \tag{22}$$

ITQ 14 A light bulb is rated at 60 W, an electric iron at 750 W and a fan heater at 2 kW. Use Equation 21 to calculate how many joules of electrical energy are converted when each of these devices is left on for an hour. Enter your results on Table 1.

You might care to look at some of the other items of electrical equipment in your home (such as the TV, radio, cooker, etc.) and compare the rates at which they convert their supply of electrical energy to other forms. (These rates are marked on the equipment in W or kW.) When you are using these pieces of household equipment, you should bear in mind that they are really just devices designed to convert the energy of the charges flowing into them into forms of energy that can be used to do various jobs.

SUMMARY OF SECTION 9

1 The only way of deciding whether or not an object is charged is to see whether it interacts with another object that is known to be charged. An uncharged object will not experience any electrostatic force, but such a force always exists between two stationary charged objects. If the objects carry charges of the same sign this force will be repulsive, whereas if the objects carry charges of opposite signs it will be attractive. The SI unit of charge is the coulomb (C).

2 The magnitude of the electrostatic force F_{el} between two point charges of magnitude Q_1 and Q_2 separated by a distance r is given by Coulomb's law,

$$F_{el} = A\,\frac{Q_1 Q_2}{r^2}$$

where A is a universal constant. The direction of the force is along the line joining the two charges.

3 When a charge Q moves through a voltage difference ΔV, the electrical energy transferred is

$$\Delta E_{el} = Q\,\Delta V$$

The SI unit of voltage difference is the volt (V).

4 The rate of flow of charge past a given point in an electrical circuit is called the current at that point. The SI unit of electric current is the amp (A):

$$1\ \text{A} = 1\ \text{C s}^{-1}$$

5 The rate at which energy is converted from one form into another is called power. The SI unit of power is the watt (W):

$$1\ \text{W} = 1\ \text{J s}^{-1}$$

The 'power rating' is marked on most household gadgets designed to run on mains electricity.

SAQ 11 A constant current of 0.2 A flows for one minute in the wires connecting a torch bulb to its battery. How much charge flows in that time?

SAQ 12 A constant current of 40 A flows in the wires that connect a 12-V car battery to the car's starter motor. Calculate the electrical energy transferred to the motor in 5 s.

SAQ 13 An electrical device is connected to a supply of electricity rated at ΔV volts and a current of I amps flows in the circuit for 1 second. Use Equations 19, 20 and 21 to derive an expression for the power P of the device.

10 ENERGY—AN OVERVIEW

When the concept of energy was first developed in the early part of the 19th century, it was confined to mechanical energy—kinetic, gravitational and strain energies. Joule then showed how this concept could be extended, by demonstrating that heat is a form of energy transfer and that conversion of mechanical energy could produce a heating effect. Since then, the list of energy types has continued to grow, within the framework set by the law of conservation of energy. This conservation law, although rooted in experiment, is also a basic tenet of scientific faith: if the known types of energy are not adequate to balance the observed energy inputs and outputs of a process, then a new form of energy transfer, or conversion, will immediately be postulated to account for the difference. However, every such extension to the scheme must then be capable of being applied in a consistent, quantitative way to other processes. So far, all the proposed additional forms of energy have been successful in this regard: conservation of energy does provide an internally consistent framework for our understanding of the Universe.

As you will see in Unit 10, Einstein was awarded the Nobel Prize in physics, not for his famous theory of relativity, but for earlier work on the nature of light. In fact, the law of conservation of energy was a crucial step in the great conceptual leap Einstein made in predicting the behaviour of light in particular circumstances. Unit 10 also describes how the law of

conservation of energy and the law of conservation of momentum, taken together, were used to gain further insight into the nature of light. In later Units you will come across further examples of discoveries arising from an application of conservation laws. The conservation of energy is a cornerstone of our modern understanding of how nature operates.

OBJECTIVES FOR UNIT 9

After you have worked through this Unit, you should be able to:

1 Explain the meaning of, and use correctly, all the terms flagged in the text.

2 Describe the various energy transfers and energy conversions in a given sequence of events. (*ITQs 1 and 5, SAQs 1 and 2*)

3 State the law of conservation of energy and apply it to a variety of energy conversions. (*ITQs 2, 3 and 9, SAQs 3 and 7–9*)

4 Recall and use correctly the equation $\Delta E = F\ \Delta x$. (*ITQ 5 and SAQ 4*)

5 Recall (or be able to derive) the dimensions of energy; be able to use a consistent set of units in order to calculate energies in joules; and, given the appropriate conversion factor, be able to convert energies from electronvolts or kilocalories to joules, and vice versa. (*ITQs 4, 6 and 7, SAQ 5*)

6 Recall, and be able to apply, the equation $\Delta E_g = mg\ \Delta h$. (*ITQs 5 and 9, SAQs 5 and 7*)

7 Recall, and be able to apply, the equation $E_k = \frac{1}{2}mv^2$. (*ITQ 8, SAQs 6, 7 and 9*)

8 Recall that kinetic energy is conserved in elastic collisions and that total momentum is conserved in any collision not involving unbalanced forces; be able to apply these facts to simple two-body collisions. (*AV sequence*)

9 Recall, and be able to apply, the equation $\Delta Q = mc\ \Delta T$. (*ITQ 9, SAQs 8 and 9*)

10 Recall that the average kinetic energy of the atoms in a substance increases with increasing temperature. (*ITQ 10, SAQ 10*)

11 Relate changes in internal energy and/or temperature to heat transfer, to changes of state of a substance and to the motion of atoms within that substance. (*ITQ 10, SAQ 10*)

12 Recall that charge can be either positive or negative and that electric current is defined as the rate of flow of charge. (*SAQs 11 and 12*)

13 Recall, and be able to apply, Coulomb's law. (*ITQs 11 and 12*)

14 Recall, and be able to apply, the equation $\Delta E_{el} = Q\ \Delta V$. (*ITQ 13 and SAQ 12*)

15 Recall that power is defined as the rate of transfer of energy, and be able to relate power to current and potential difference in simple situations. (*ITQ 14, SAQ 13*)

ITQ ANSWERS AND COMMENTS

ITQ 1 (a) In a coal-burning power station, the chemical energy released during combustion is converted to internal energy in a furnace, which is used to heat water to produce steam. The steam drives a turbine and the kinetic energy of the turbine is converted to electrical energy in a generator. This is converted to light energy in the bulbs in your house.

(b) In a hydro-electric plant, the energy of moving water is harnessed: the water falls over a cascade of some sort and then flows through the turbines. Just as in the case of the falling ball, gravitational energy is converted to kinetic energy as the water pours down the falls, and this kinetic energy is transferred to the turbines. Thereafter, the sequence of events is as in (a).

ITQ 2 If you were constructing a model of the bouncing ball, and considering only the conversion of gravitational energy to kinetic energy, you could take the ball on its own as the physical system. However, if you were interested in applying the law of conservation of energy to a real ball, you would have to take account of the fact that the ball interacts with the ground when it bounces, and with the air (because of air resistance and the transmission of sound energy). To describe fully all the energy conversions, you would therefore have to consider a physical system comprising the ball, the ground near the point of impact and the surrounding atmosphere.

ITQ 3 A belief in the law of conservation of energy would lead you to conclude that four units of energy had been converted into other forms—for example light energy (the element of the fire will glow red), the internal energy of the atmosphere surrounding the fire, and possibly sound energy.

ITQ 4 $(\text{mass}) \times (\text{length})^2 \times (\text{time})^{-2}$.

The dimensions of energy must be those of (force × distance). From Unit 3 you should remember that the dimensions of force are those of (mass × acceleration) and that the dimensions of acceleration are $(\text{length})/(\text{time})^2$.

The dimensions of force are thus $(\text{mass}) \times (\text{length}) \times (\text{time})^{-2}$. Because the dimensions of distance are (length), the dimensions of energy must be

$$(\text{mass}) \times (\text{length})^2 \times (\text{time})^{-2}$$

ITQ 5 Chemical energy (from the food you have digested) has been converted into the kinetic energy of the bag (while it is moving) and of your body (while performing the lifting operation), and into an increase in the gravitational energy of the bag, which it retains at the end of the sequence of conversions.

The magnitude of the weight of the bag of potatoes is given by Newton's second law:

$$|\text{weight}| = \text{mass} \times |\text{acceleration due to gravity}|$$
$$= 5\ \text{kg} \times 10\ \text{m s}^{-2}$$
$$= 50\ \text{N}$$

This weight acts vertically downwards and you have to exert an upward force of equal magnitude in order to lift the bag at constant speed. (In practice you have to supply an upward force slightly greater than this in order to *accelerate* the bag, i.e. to get it moving from its state of rest, but this additional amount of force only gives the bag *kinetic* energy, which it does not have at the end of the manoeuvre.) From Equation 3, the energy transferred is given by

$$\text{energy transferred} = |\text{force}| \times \text{distance moved}$$

In this case, the energy change ΔE is therefore given by

$$\Delta E = 50\ \text{N} \times 1\ \text{m}$$
$$= 50\ \text{J}$$

ITQ 6 2.5×10^5 J.

Since 1 kcal $\approx 4.2 \times 10^3$ J,

the energy available from a slice of bread is

$$60\ \text{kcal} \approx 60\ \text{kcal} \times (4.2 \times 10^3\ \text{J kcal}^{-1})$$
$$\approx 250 \times 10^3\ \text{J}$$

ITQ 7 The dimensions of speed are (length/time), i.e. $(\text{length}) \times (\text{time})^{-1}$. Therefore the dimensions of $(\text{speed})^2$ are $(\text{length/time})^2$, i.e. $(\text{length})^2 \times (\text{time})^{-2}$.

Thus the dimensions of $(\text{mass}) \times (\text{speed})^2$ are $(\text{mass}) \times (\text{length})^2 \times (\text{time})^{-2}$, which you saw in ITQ 4 are the dimensions of energy.

ITQ 8 2.6×10^5 J.

Equation 7 is the appropriate one to use

$$E_k = \tfrac{1}{2}mv^2$$

Remember that all quantities must be expressed in SI units in order to obtain an answer in joules! In particular, the speed v must be converted to metres per second:

$$80\ \text{km h}^{-1} = \frac{80 \times 10^3\ \text{m}}{3\,600\ \text{seconds}}$$
$$= \frac{800}{36}\ \text{m s}^{-1}$$

So

$$E_k = \frac{1}{2} \times 1\,050\ \text{kg} \times \left(\frac{800}{36}\ \text{m s}^{-1}\right)^2$$
$$\approx 2.6 \times 10^5\ \text{J}$$

ITQ 9 (a) 5.3×10^3 J.

Every time one weight falls, the gravitational energy converted is

$$\Delta E_g = mg\ \Delta h$$
$$= 13.2\ \text{kg} \times 9.8\ \text{m s}^{-2} \times 1.02\ \text{m}$$
$$\approx 132\ \text{J}$$

Two weights fall on each run, so the total kinetic energy transferred by both weights over 20 runs is

$$2 \times 132\ \text{J} \times 20 = 5.28 \times 10^3\ \text{J}$$

Note that to be consistent with the data, the final answer must be given to two significant figures, i.e. 5.3×10^3 J.

(b) $4.2 \times 10^3\ \text{J kg}^{-1}\ \text{K}^{-1}$.

Assuming that all this energy is transferred to the water in the form of heat, then

$$\Delta Q = 5.28 \times 10^3\ \text{J} = mc\ \Delta T$$

and the specific heat of the water is

$$c = \Delta Q/m\ \Delta T$$

$$= \frac{5.28 \times 10^3\ \text{J}}{3.2\ \text{kg} \times 0.39\ \text{K}}$$

$$\approx 4.2 \times 10^3\ \text{J kg}^{-1}\ \text{K}^{-1}$$

ITQ 10 Only statement (c) is true.

(a) is false: the temperature of a substance will only rise under these circumstances provided there is no change of state (i.e. provided the liquid does not boil).

(b) is false: the *average* speed (or average kinetic energy) of all the atoms is related to the temperature of the gas, but it is not possible to predict whether an individual atom will be moving more quickly or more slowly than the average.

(c) is true.

(d) is false: an increase in internal energy only corresponds to an increase in temperature if no change of state occurs.

ITQ 11 $\text{N m}^2\ \text{C}^{-2}$.

Rearranging Equation 16 gives an expression for A

$$A = \frac{F_{\text{el}} \times r^2}{Q_1 Q_2}$$

In SI units, F_{el} is measured in newtons, r^2 in metres^2, and Q_1 and Q_2 in coulombs. The SI units of A must therefore be $\text{N m}^2/\text{C}^2$, i.e. $\text{N m}^2\ \text{C}^{-2}$.

ITQ 12 2.3×10^{-8} N; 5.5×10^{-51} N

From Equation 16, the magnitude of the electrostatic force between the two electrons is

$$\frac{8.99 \times 10^9\ \text{N m}^2\ \text{C}^{-2} \times (1.6 \times 10^{-19})^2\ \text{C}^2}{(1.0 \times 10^{-10})^2\ \text{m}^2}$$

$$\approx 2.3 \times 10^{-8}\ \text{N}$$

From Equation 17, the magnitude of the gravitational force between the two electrons is

$$\frac{6.672 \times 10^{-11}\ \text{N m}^2\ \text{kg}^{-2} \times (9.1 \times 10^{-31})^2\ \text{kg}^2}{(1.0 \times 10^{-10})^2\ \text{m}^2}$$

$$\approx 5.5 \times 10^{-51}\ \text{N}$$

Remember that to specify the forces completely, their directions must also be stated! In both cases the forces act along the line joining the two charges, but the electrostatic force is repulsive, whereas the gravitational force is attractive.

Comment The magnitude of the electrostatic force between these two electrons is about 10^{43} times greater than the magnitude of the gravitational force between them. Gravitational effects between such sub-atomic particles are completely swamped by electrostatic effects.

ITQ 13 1.602×10^{-19} J.

From Equation 19, the energy transferred must be

$$\Delta E_{\text{el}} = Q\ \Delta V$$

$$= 1.602 \times 10^{-19}\ \text{C} \times 1\ \text{V}$$

$$= 1.602 \times 10^{-19}\ \text{J}$$

ITQ 14 $2.2 \times 10^5\ \text{J hour}^{-1}$; $2.7 \times 10^6\ \text{J hour}^{-1}$; $7.2 \times 10^6\ \text{J hour}^{-1}$.

Since $1\ \text{W} = 1\ \text{J s}^{-1}$ and 1 hour = 3 600 s, the amounts of energy converted will be—

for the bulb: $60\ \text{J s}^{-1} \times 3\,600\ \text{s hour}^{-1}$

$$\approx 2.2 \times 10^5\ \text{J hour}^{-1}$$

for the iron: $750\ \text{J s}^{-1} \times 3\,600\ \text{s hour}^{-1}$

$$= 2.7 \times 10^6\ \text{J hour}^{-1}$$

for the heater: $2\,000\ \text{J s}^{-1} \times 3\,600\ \text{s hour}^{-1}$

$$= 7.2 \times 10^6\ \text{J hour}^{-1}$$

Motto: it costs over thirty times as much to run the heater as it does to run the light bulb for the same time!

SAQ ANSWERS AND COMMENTS

SAQ 1 When the gymnast is descending through the air, as shown in Figure 3a, gravitational energy is being continuously converted into kinetic energy. Just after she hits the trampoline she is prevented from falling any further and momentarily stops (Figure 3b): her kinetic energy is transformed into the strain energy stored by the trampoline. This strain energy is then converted back to kinetic energy and she is propelled upwards. During her upward motion, kinetic energy is converted into gravitational energy. At the highest point of her trajectory (Figure 3c), she again stops moving momentarily, all her kinetic energy having been transformed into gravitational energy.

SAQ 2 The child transfers energy to the catapult's elastic, which thereby acquires strain energy. When the stone is released, this strain energy is converted into the energy of motion, or kinetic energy, of the stone. As the stone rises towards the window, its gravitational energy will increase at the expense of its kinetic energy. There will also be a slight increase in the temperature of the stone and the surrounding air because of frictional effects: again these increases in internal energy occur at the expense of a corresponding decrease in the stone's kinetic energy.

When the stone strikes the pane of glass some of its kinetic energy is converted into strain energy of the glass. The glass then shatters as some of this energy is converted into kinetic energy of the fragments of glass so they fly all over the place. Since you would hear the glass shatter, some of the stored strain energy must also have been converted to sound energy.

SAQ 3 Energy *is* always conserved in a system as a whole. However in the domestic situation, the system is a large one, and there is plenty of scope for energy to be converted into forms that are not directly useful. For example, the electrical energy used to run an oven is not only converted into internal energy in the food, but also into internal energy in the fabric of the cooker, the air inside the oven and the air in the kitchen. What we need to do is to minimize these 'non-productive' conversions. Conservation of energy is actually irrelevant to the argument: the so-called energy-saving devices are in fact designed to save *fuel*.

SAQ 4 (a) 100 J.

The energy transferred may be calculated from Equation 3:

$$\begin{aligned}\Delta E &= F \times \Delta x\\ &= 5\ \text{N} \times 20\ \text{m}\\ &= 100\ \text{J}\end{aligned}$$

(b) No. In practice, the kinetic energy of the trolley would be less than 100 J, because some of the energy transferred would be converted to forms of energy other than kinetic (internal energy in the trolley wheels, sound energy if the trolley rattles, etc). The total amount of energy is, however, always conserved.

SAQ 5 32 kcal.

When he climbs the Tower, the tourist's change in gravitational energy will be

$$\begin{aligned}\Delta E_g &= mg\ \Delta h\\ &= 80\ \text{kg} \times 10\ \text{m s}^{-2} \times 170\ \text{m}\\ &= 1.36 \times 10^5\ \text{J}\\ &= \frac{1.36 \times 10^5\ \text{J}}{4.2 \times 10^3\ \text{J kcal}^{-1}}\\ &\approx 32\ \text{kcal}\end{aligned}$$

Given the assumption stated in the question, he works off (in energy terms) only about 10% of what he consumed. So it takes a lot of exercise to make up for one small indulgence!

The assumption represents a considerable simplification of the real situation and will not be valid in practice. For one thing it ignores the large amount of kinetic energy the tourist has while actually moving upwards. In addition, most people would get pretty warm climbing that number of stairs, so the tourist will 'use' more than 1.36×10^5 J of energy and convert much of the excess to internal energy.

SAQ 6 (a) 30 J.

The ball's kinetic energy is given by Equation 7:

$$E_k = \tfrac{1}{2}mv^2$$

So when it reaches the wicket-keeper, the ball's kinetic energy will be

$$\begin{aligned}&0.5 \times 0.15\,\text{kg} \times (20\ \text{m s}^{-1})^2\\ &= 30\ \text{J}\end{aligned}$$

(b) 5 m.

In this case, kinetic energy is converted into gravitational energy. The ball has its maximum kinetic energy, and hence its maximum speed, when it leaves the fielder's hands, and zero speed when it reaches its maximum height. The change in height Δh can therefore be calculated by rearranging Equation 8 (or, more simply, the preceding equation) to give

$$\begin{aligned}\Delta h &= v_{max}{}^2/2g\\ &= \frac{(10\ \text{m s}^{-1})^2}{2 \times 10\ \text{m s}^{-2}}\\ &= 5\ \text{m}\end{aligned}$$

SAQ 7 32 m s^{-1}.

When a skier moves from the highest point of the ramp to the lowest point, his change in gravitational energy is given by

$$\Delta E_g = mg\ \Delta h$$

where Δh is 50 metres.

If the skier arrives at the bottom of the ramp with a

speed v, then his kinetic energy at that point will be

$$E_k = \tfrac{1}{2}mv^2$$

Assuming no friction or air resistance (i.e. assuming that all the gravitational energy he has at the top is converted to kinetic energy at the bottom),

$$E_k = \Delta E_g$$

i.e. $\tfrac{1}{2}mv^2 = mg\,\Delta h$

and $v = \sqrt{2g\,\Delta h}$

$$= \sqrt{2 \times 10\ \text{m s}^{-2} \times 50\ \text{m}}$$

$$\approx 32\ \text{m s}^{-1}$$

Clearly, neither of the assumptions made above is really valid. Much of the skill of the ski-jumper lies in correctly waxing the skis to reduce friction and in adopting a good 'aerodynamic' position. Even so, the effects of friction and air resistance cannot be eliminated altogether. In addition, the speed at which the skier launches himself is greater than the above calculation suggests because he 'springs' off the end of the ramp, so increasing his kinetic energy.

SAQ 8 You wish to know how much energy is required to raise the temperature of the milk from room temperature to the temperature at which it boils. You would, therefore, need to know the room temperature T_{room} and the boiling temperature of milk T_b. Also, you would need to know the mass m of the milk, and its specific heat c_m. Then the energy required to raise its temperature by $(T_b - T_{\text{room}})$ is $m \times c_m \times (T_b - T_{\text{room}})$. In addition, you would have to find out how much heat energy is required to heat the saucepan from room temperature to the temperature at which milk boils. You would therefore need to know the mass of the saucepan and its specific heat.

Finally, you would need to take into account the energy 'lost' to the surrounding atmosphere. To find the total amount of energy required, you would need to use the law of conservation of energy:

energy supplied = heat required to raise the temperature of the milk and saucepan
+ energy 'lost' to surroundings

SAQ 9 0.17 K.

Using the usual symbols, the gravitational energy lost by the water is $mg\,\Delta h$ and this is equal to the kinetic energy gained during the fall. If all that kinetic energy is converted to heat when the water reaches the bottom, then

$$mg\,\Delta h = mc\,\Delta T$$

So the temperature difference, ΔT, between top and bottom is

$$\Delta T = g\,\Delta h/c$$

$$= \frac{9.8\ \text{m s}^{-2} \times 73.2\ \text{m}}{4.2 \times 10^3\ \text{J kg}^{-1}\ \text{K}^{-1}}$$

$$\approx 0.17\ \text{K}$$

(To work out the units remember that $1\ \text{J} = 1\ \text{N m}$ and that $1\ \text{N} = 1\ \text{kg m s}^{-2}$.)

It would be difficult to expect to measure such a temperature difference in practice, because more heat will probably be transferred away from the water by spray and evaporation than is transferred to it by the process described in the question.

SAQ 10 The red-hot poker is a solid that consists of atoms moving about fixed points (Figure 20). The water is a liquid that consists of molecules moving around as shown in Figure 21.

The temperature of the poker would be well above that of the water. When the poker is plunged into the water, the poker cools down and the water warms up—the average energy (and hence the average speed) of the atoms in the poker decreases and the average energy (and hence the average speed) of the molecules in the water increases. There has been a flow of energy between the poker and the water.

Steam may be given off after a certain amount of energy has been transferred to the water, if some of the water molecules acquire enough energy to escape from the forces that hold them together in the liquid.

SAQ 11 12 C.

From Equation 20 the current I that flowed in the wires is defined as the rate at which the charge Q flowed through them over time t,

$$I = Q/t$$

Thus,

$$0.2\ \text{A} = \frac{Q}{60\ \text{s}}$$

and therefore

$$Q = 60\ \text{s} \times 0.2\ \text{C s}^{-1} = 12\ \text{C}$$

SAQ 12 2.4×10^3 J.

The electrical energy ΔE_{el}, that is transferred is given by Equation 19:

$$\Delta E_{el} = Q\,\Delta V$$

where Q is the charge that flows in the wires and where ΔV is the voltage difference. Since 40 A flow for 5 s, the total amount of charge Q that flows through the wires is (from Equation 20):

$$Q = 40\ \text{A} \times 5\ \text{s} = 2 \times 10^2\ \text{C}$$

Hence, $\Delta E_{el} = 2 \times 10^2\ \text{C} \times 12\ \text{V} = 2.4 \times 10^3$ J.

SAQ 13 $P = I\,\Delta V$.

The energy ΔE_{el} transferred to the device is given by Equation 20, $\Delta E_{el} = Q\,\Delta V$, where Q is the charge that flows through the connecting wires in time t. Equation 20 says that the current I is given by Q/t. Hence, substituting into Equation 19:

$$\Delta E_{el} = It\,\Delta V$$

The power-rating P of the device is defined as the rate at which it converts energy. Hence,

$$P = \Delta E_{el}/t = I\,\Delta V$$

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Figure 1 Gary Rees; *Figure 17* BBC Hulton Picture Library; *photograph, p. 22* S & G Press Agency Ltd.